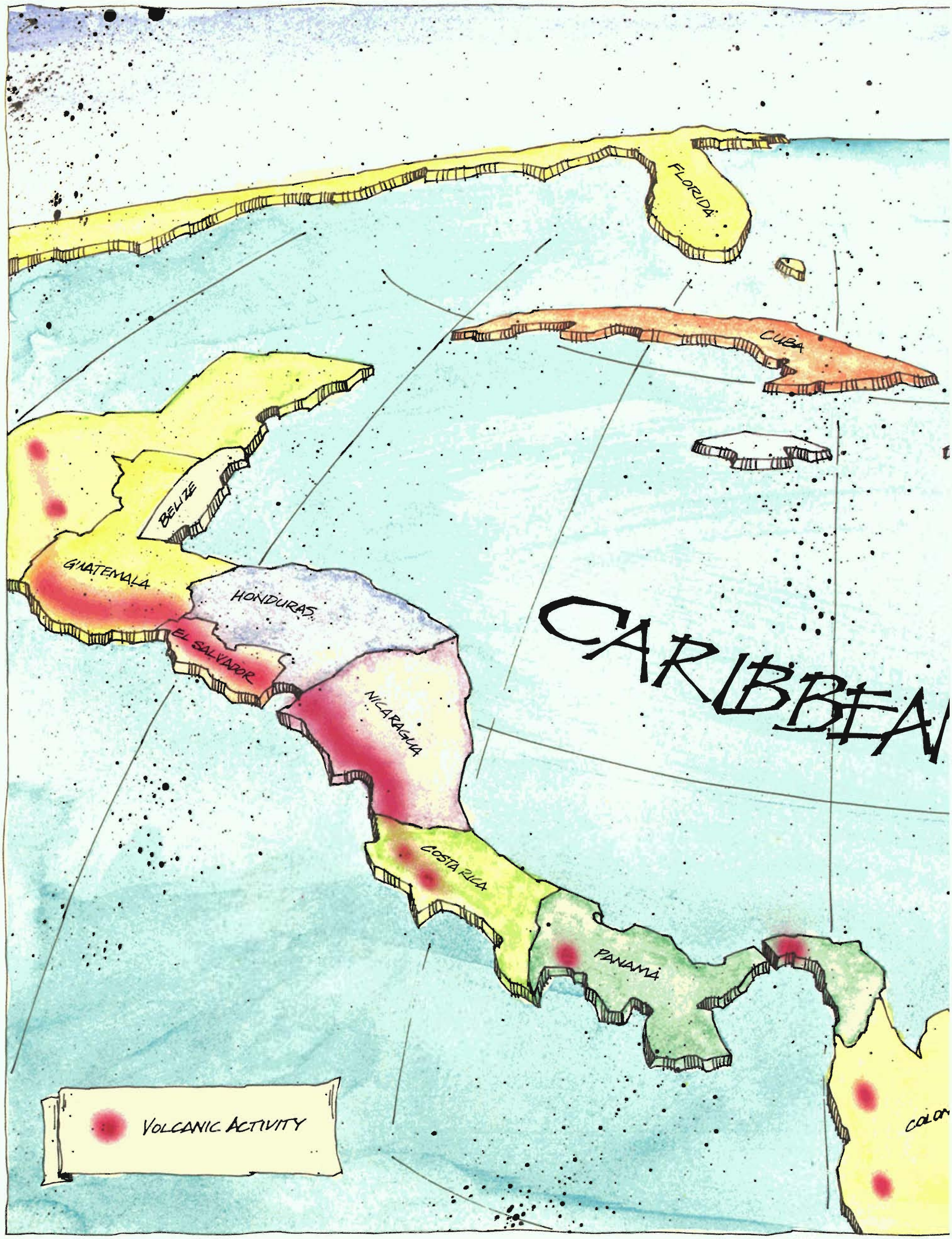
FLORIDA
CUBA
BELIZE
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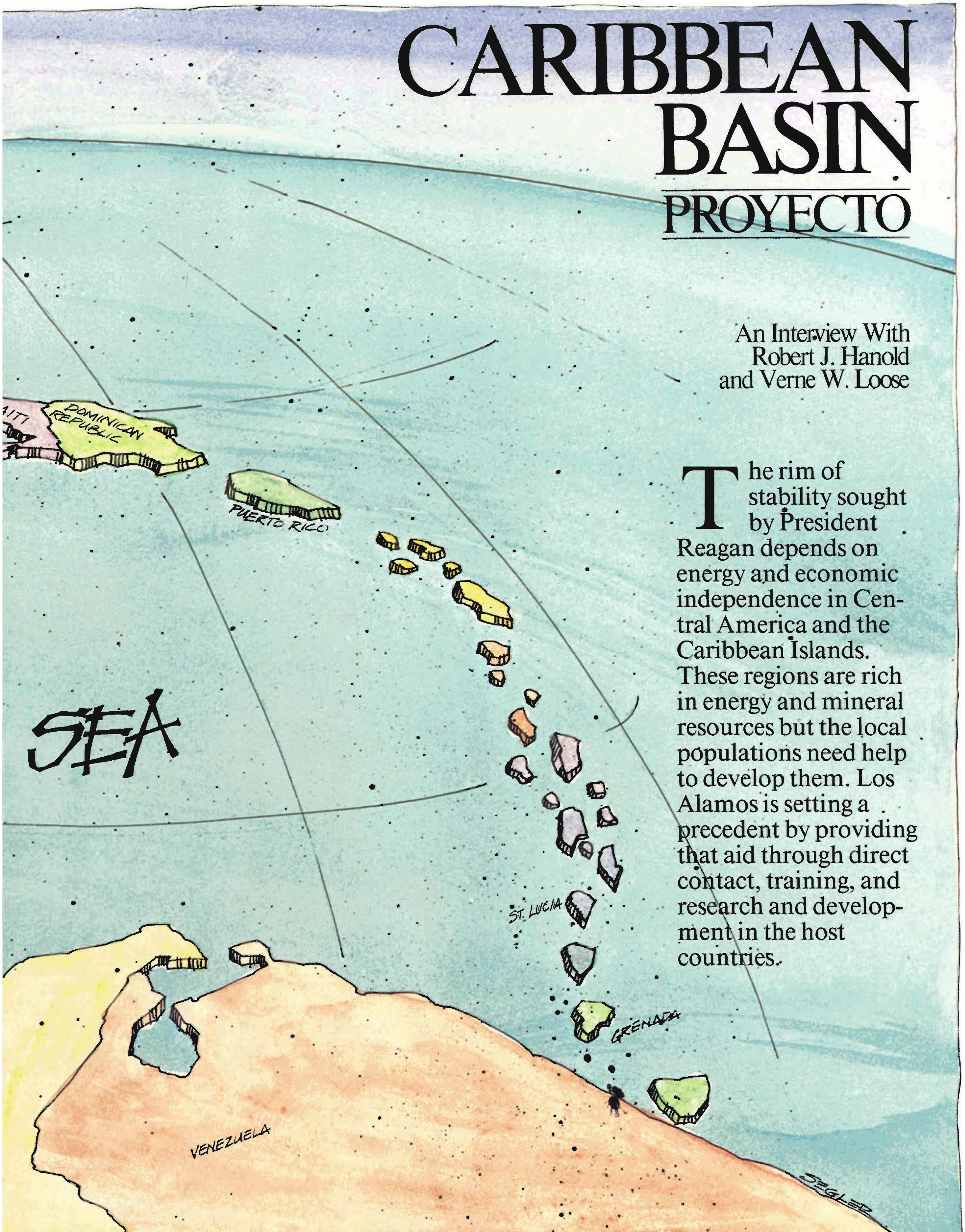
HONDURAS
EL SALVADOR
NICARAGUA
CARIBBEAN
COSTA RICA
PANAMA
VOLCANIC ACTIVITY

CARIBBEAN BASIN PROYECTO

An Interview With
Robert J. Hanold
and Verne W. Loose



The rim of stability sought by President Reagan depends on energy and economic independence in Central America and the Caribbean Islands. These regions are rich in energy and mineral resources but the local populations need help to develop them. Los Alamos is setting a precedent by providing that aid through direct contact, training, and research and development in the host countries.

Science: *The Los Alamos travel office is busy sending scientists and equipment to the Caribbean Basin. What is going on there?*

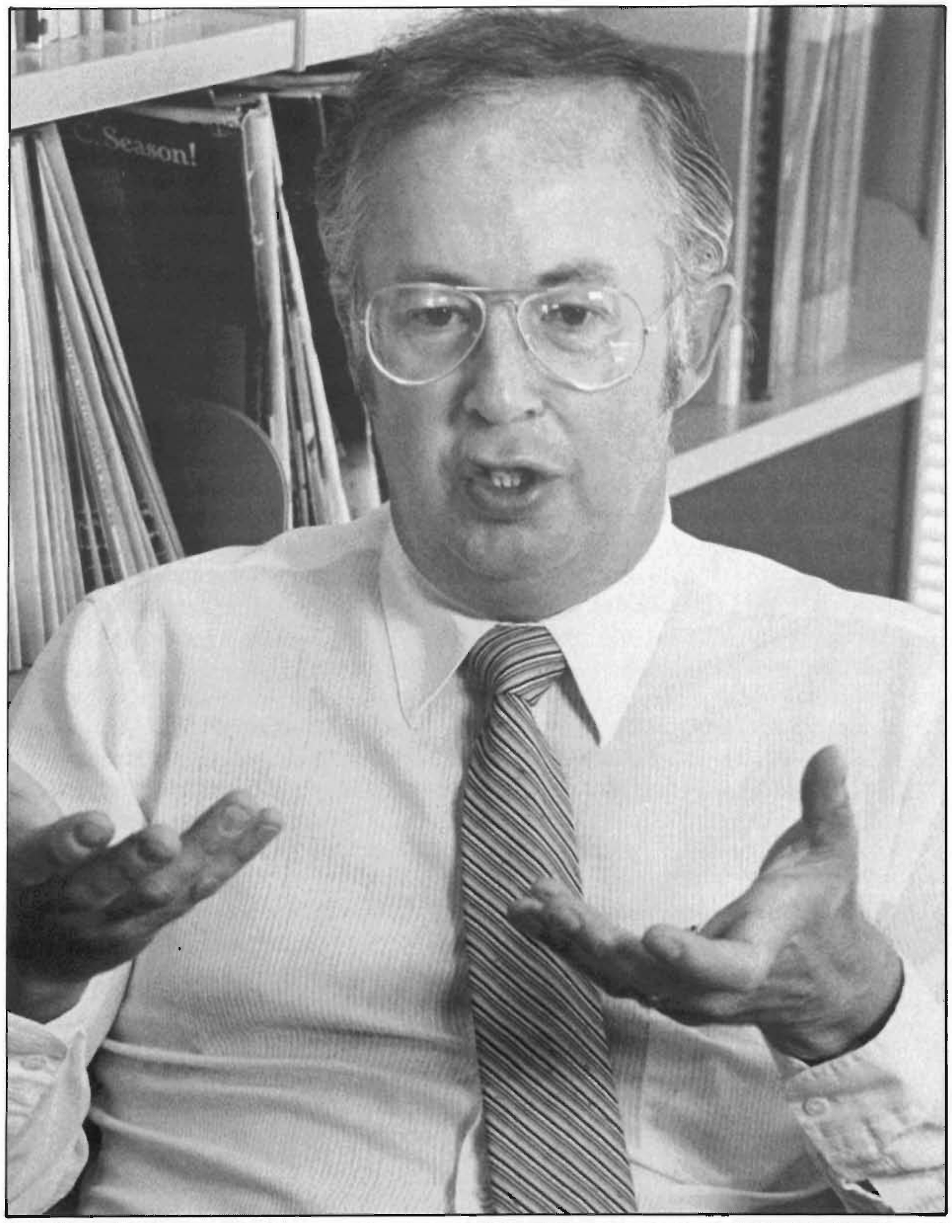
Loose: We are involved in a project designed to address the energy problems of certain countries there, the main problem being the need to import large quantities of petroleum and the consequent buildup of huge foreign debts.

Science: *Are the economies of these countries very weak?*

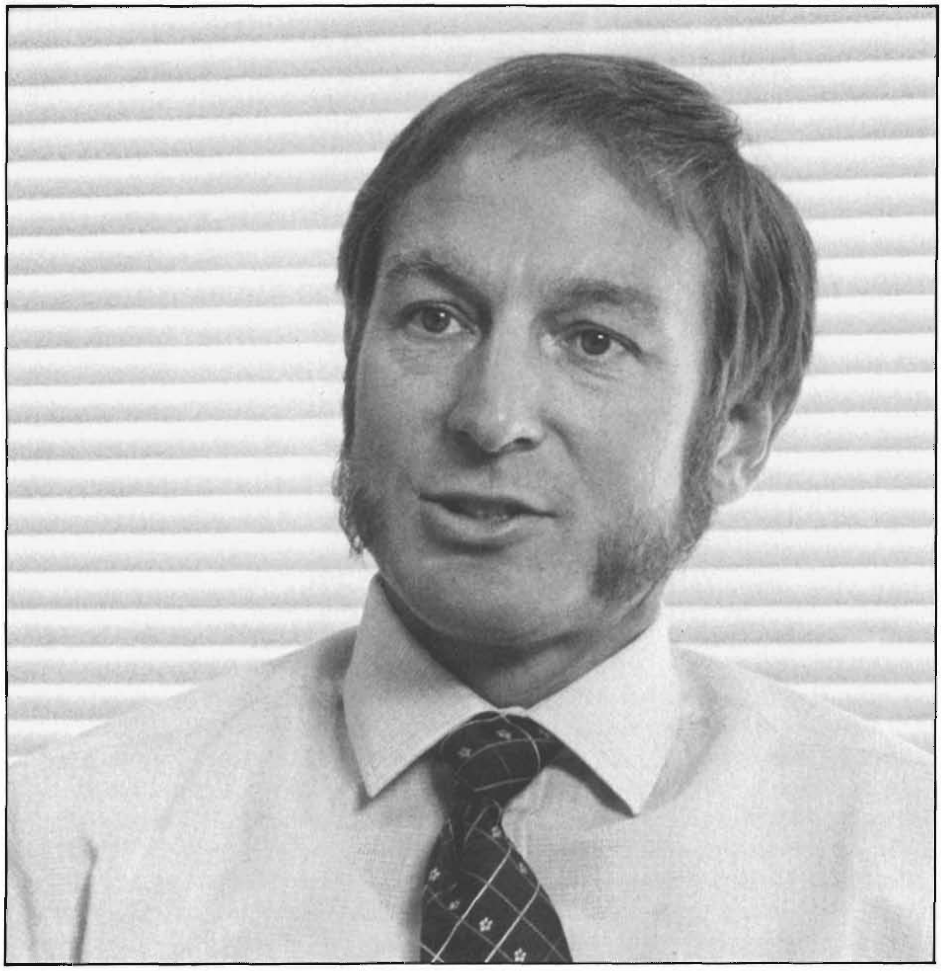
Loose: They are fragile. Between World War II and 1978 economic expansion was fairly rapid due to periodic booms in the price of their agricultural products, increases in manufacturing, and heavy foreign borrowing. Since 1978, however, commodity prices have fallen, and manufacturing has slowed down due to worldwide recession. Sustained insurgent activity in Nicaragua, El Salvador, and Guatemala has contributed an additional burden to the economies of those countries. Moreover, the cost of imported petroleum grew so rapidly after the Arab oil embargo in 1973 and the Iranian cutback of 1979 that by the early eighties 20 to 25 percent of every dollar earned from exports went to buy petroleum. It is this acute economic situation that we are trying to remedy.

Hanold: St. Lucia is a good example. This Caribbean island generates all of its electric power with diesel engines. When we made our first visit there in 1983, the import of diesel fuel was imposing a burden in excess of a million dollars a month. That's not much in our economy, but for a small Caribbean island with a total population of 120,000 and a relatively small industrial economy, the burden is intolerable. The prime minister of St. Lucia was aware of the efforts of the United States to develop alternative forms of energy. Since St. Lucia is entirely volcanic in nature, he knew it would probably have an excellent geothermal resource that, if developed properly, might displace the imported petroleum.

Science: *Who is the prime minister?*



Bob Hanold, Program Manager for International Energy Activities in the Earth and Space Sciences Division, is responsible for the technical management of the geothermal projects in Central America and the Caribbean. He accepted a postdoctoral fellowship at Los Alamos in 1966, immediately after earning a Ph.D. in engineering science at Case Institute of Technology, and became a staff member in 1968. He has extensive experience in research and development of all aspects of geothermal projects, including well stimulation by hydraulic fracture and chemical treatment, chemical scale control, pumping systems, fracture diagnostics, and high-temperature instrumentation. He has also been a leader in the development of cost-shared field experiments with industry. His warm personality combined with his vast technical knowledge makes him a very valuable asset to technology transfer initiatives.



Verne Loose is Program Manager for International Initiatives in the office of the Assistant Director for Industrial and International Initiatives and is also Program Manager of the Central American Energy Resources Project. He earned his Ph.D. in natural resources and energy economics from the University of British Columbia and then worked for the government of British Columbia as an energy economist. He has extensive experience in evaluation of natural resources development projects. Since joining the Laboratory in 1977, he has been doing research in energy economics, including analyses of utility investment and oil and gas substitution and mathematical studies of optimal oil and gas reservoir production. Before becoming Program Manager for International Initiatives, he was Leader of the Economics Group for three-and-a-half years. He has spearheaded the studies of energy economics for the Central American project during the past two-and-a-half years.

Loose: His name is John Compton. He is a very capable and charismatic leader and a very delightful gentleman. He was trained as an attorney in England and is also the owner of a banana plantation. His ancestors were slaves under the English. The control of St. Lucia, like that of many other Caribbean islands, has alternated back and forth during the last two or three hundred years among the English, the French, and the Spanish. Most recently St. Lucia was an English protectorate. English is the official language, although most of the population speaks a dialect of French.

Science: *Who is affected by the adverse balance of payments? The wealthy sector of the population?*

Hanold: Since imported petroleum is the source of all of the island's electricity, anyone who purchases electricity has to bear the brunt of its cost.

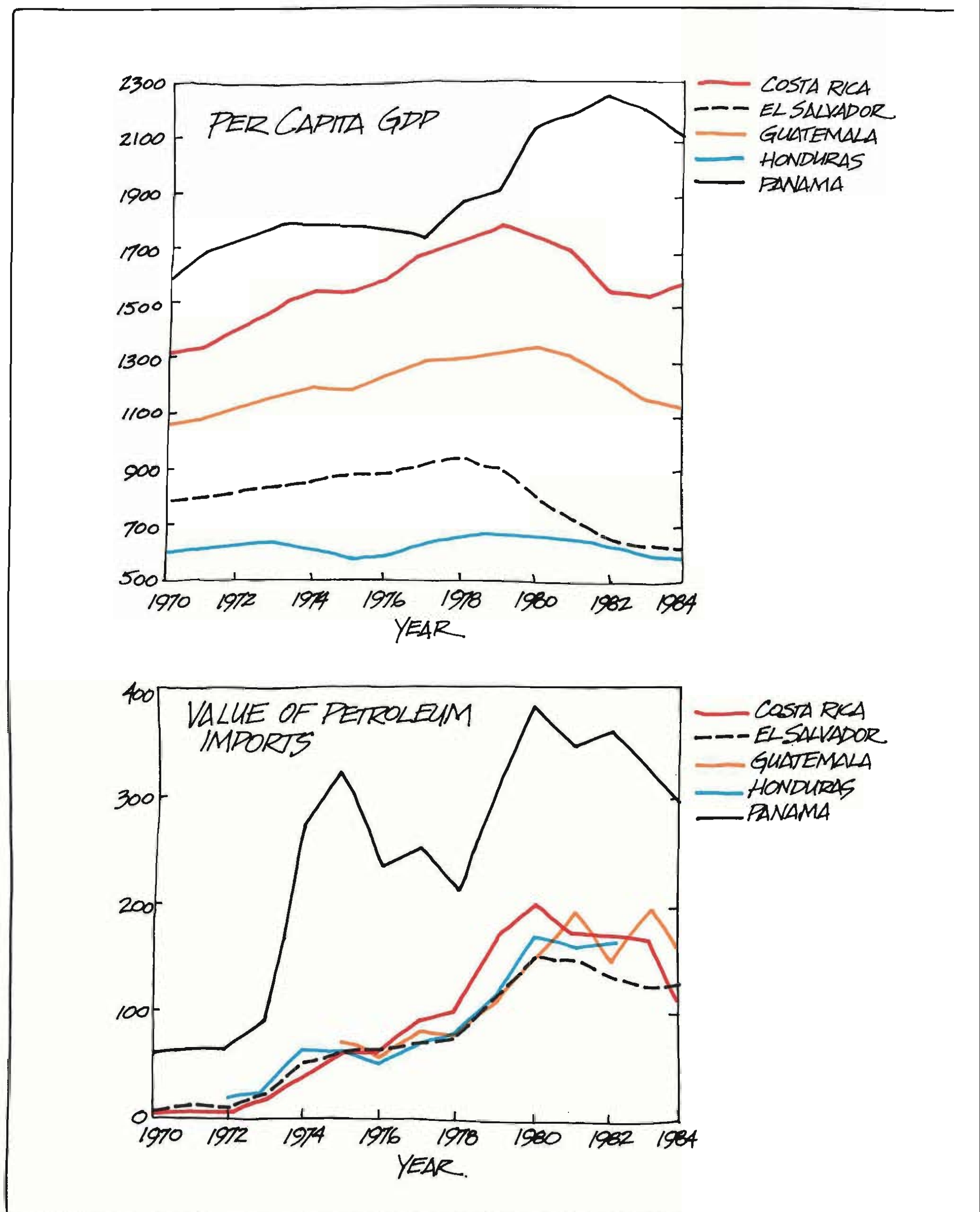
Science: *Did the Los Alamos project start with work in St. Lucia?*

Loose: Officially, yes. But Ron Lohrding, the Laboratory's Assistant Director for Industrial and International Initiatives, has been laying the groundwork for this project during the last five years or so. Initially he developed contacts with European and international energy organizations to see how the Laboratory's expertise in energy technology might be transferred to other countries. About three years ago his interest was channeled to the Caribbean islands and Central America, in part by Reagan's Caribbean Basin Initiative. This initiative was intended to develop a rim of stability in what the Monroe Doctrine defines as our nation's area of influence. Ron worked with people in Washington to find ways in which institutions like Los Alamos could help to support the president's policy. In addition, Ron and John Whetten, then leader of the Earth and Space Sciences Division, traveled extensively in the Caribbean. They visited various mission offices of the United States Agency for International Development [the AID] as well as government officials in the host countries. During that trip they met and briefed Mr. Compton. They emphasized the Laboratory's expertise in geothermal energy in part because of our hot dry rock geothermal project but mostly because they knew the prime minister was interested in geothermal development. This mutual interest led to requests in Washington on behalf of Mr. Compton for that type of technical assistance. Los Alamos secured funds from the State Department's Trade Development Program, one goal of which is to give projects a boost toward commercialization. We began to use the funds for field work at the Qualibou Caldera in St. Lucia in August 1983.

Hanold: A few months later the Kissinger Commission, the president's Bipartisan Commission on Central America, asked us to brief them on the technical assistance needs of Central America. They were particularly interested in identifying projects that would generate employment and promote economic development in the region.

Science: *Was Los Alamos the only national laboratory invited to give a briefing?*

Loose: Yes. I suppose we were chosen for several reasons—our familiarity with the Hispanic culture of the Southwest, our technical expertise in geothermal energy and economic analysis, our technical collaboration with the Petroleum Institute and the Nuclear Research Institute of Mexico, as well as our recent experience in St. Lucia. Prior to that meeting John



Whetten spent two weeks in Costa Rica with the Organization of American States to identify employment-generating projects in the energy and mineral sectors. Information gained from that mission, as well as an analysis of the region by Los Alamos, enabled Whetten to identify peat as a neglected resource in Costa Rica and possibly in other Central American countries. In addition to geothermal and peat development, we emphasized the potential for minerals development at the Kissinger Commission briefing. With the exception of Cuba, where Soviet influence is prevalent, mineral resources contribute very little to the gross national products of the Caribbean Basin countries. In contrast, minerals developed with Soviet investments account for a substantial fraction of Cuba's gross national product.

Hanold: Training the local population was another issue we discussed with the Commission. It is of paramount importance in any technical assistance project. The Soviets know this and are sponsoring graduate and undergraduate training of many Central American students.

Loose: Following the Kissinger Commission briefing we prepared a proposal to the AID for $10.2 million to provide technical assistance in energy development, mineral development, and energy and economic planning to five Central American countries—Honduras, Costa Rica, El Salvador, Panama, and Guatemala. The goals are to identify resources, provide technical training, and help find funding for development.

Science: *Does this project have any precedents?*

Loose: It is new for Los Alamos, and it is a little different from most American technical assistance projects. Usually the AID mission office in a country gets ideas from the local government personnel as to what types of technical assistance would be beneficial. In this case Los Alamos helped to identify the needs and to convince the AID mission offices of the benefits to be gained from meeting them.

Hanold: Also, the technological level of the project is higher than is typical.

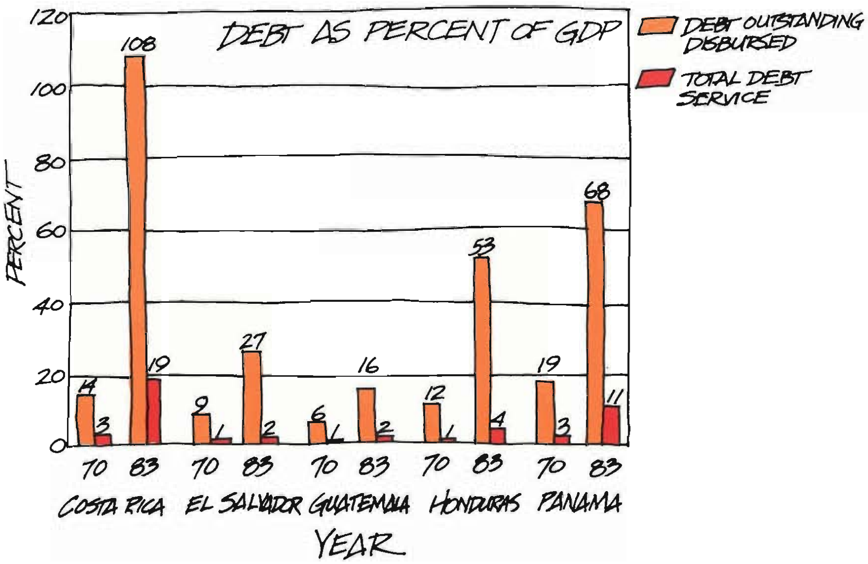
Loose: The AID usually tries to help the poorest of the poor. They focus on basic human needs, such as health, potable water, sanitation, and education. In contrast, this project, which addresses the middle ground of technology, is focused on the industrial sector of the country. It is being done in the spirit of the Alliance for Progress of the early sixties, which gave assistance to Latin America.

Science: *Did you have to convince the AID that the project was appropriate to their goals?*

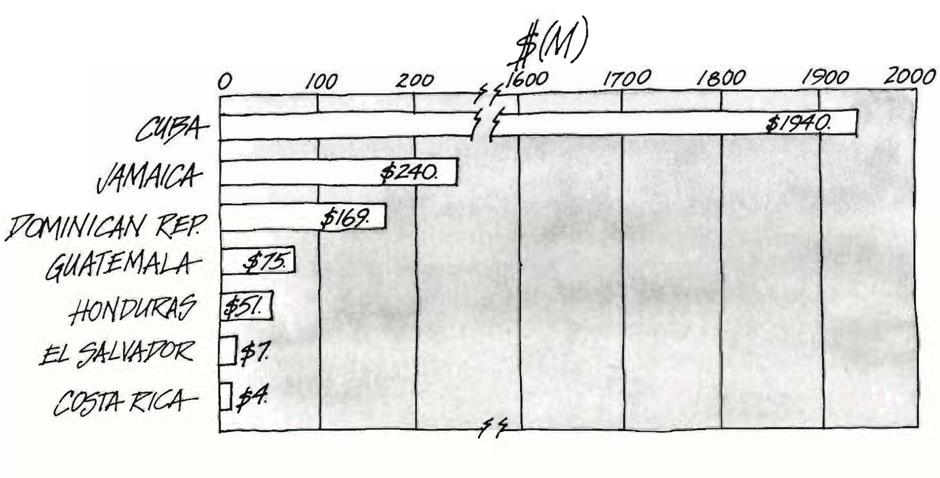
Loose: Yes, we had to create a demand for the project, and John Compton was very helpful in this regard by giving us a concrete example of what we could accomplish.

Hanold: Our job was made easier in St. Lucia because we had been preceded by technical delegations from other countries who had investigated the possibility of geothermal power. The Italians had done so in the early eighties. Before that the English had done a great deal of pioneering work on geothermal manifestations. The government of St. Lucia had seen a number of starts and stops and was anxious that the project be brought to fruition. With the basic geologic data already at hand, we were to choose the locations for drilling the geothermal wells and provide the government with enough confidence to solicit funds for drilling the wells and constructing the geothermal power plant.

Science: *Can you guarantee that the projects you start will reach fruition?*



Recent economic history of five Central American countries. The per capita gross domestic product (GDP) is the best indicator of the standard of living in these countries. The GDP is the value of all goods and services produced annually by citizens of a country (the gross national product) plus the net foreign income (the value of goods produced in a country by foreign companies minus the income earned by citizens living and working abroad). (The per capita GDP data were obtained from the Inter-American Development Bank and the World Bank.) Between 1970 and about 1980, the per capita GDP in these countries was on the rise as a result of industrial development and higher prices for agricultural commodities. The dramatic increase in oil prices after the Arab oil embargo of 1973 and the reliance on public borrowing to support economic growth led to the accumulation of huge foreign debts. (The foreign debt data were obtained from the World Bank.) Since 1980 the worldwide recession has led to a decrease in the per capita GDP and in the ability of these countries to import foreign oil.



Income generated from mineral resources. The larger income in Cuba compared with other Caribbean Basin countries is due to Soviet investment.

Hanold: There are no guarantees, but we will make every effort possible to finish what we start. We have already made dramatic strides in St. Lucia. Our work was accepted by the government of St. Lucia as a sufficient basis to begin drilling. Grants for about $5 million have now been obtained, from the United Nations and the AID, to drill three geothermal wells. Engineers from Los Alamos have been in St. Lucia putting together the plans for drilling, which will start sometime in mid 1986.

Of course drilling wells, whether for oil or geothermal water, is always a risky business. We're not home free until we hit a reservoir that has a good heat source and a good plumbing system through which the hot water can reach the well.

Science: *If the drilling is successful, will the project then be self-supporting?*

Loose: Self-supporting in the sense that money from the sale of electricity will pay for the power plant and its operation. The grants Bob mentioned will pay for the drilling. I would like to emphasize that the Los Alamos project is not focusing on paper studies that may end up collecting dust on somebody's shelf. We are focusing on real investments in energy production capacity. One of our aims is to establish a network of contacts in both the United States and the host countries to interest private investors in development. Private investors are interested in the St. Lucia development, and we would like to see that happen in Central America.

Hanold: Organizations from other countries have already approached us about investments in St. Lucia. For example, the Japanese, who are very strong in manufacturing equipment for electric power generation, requested information about the characteristics of the geothermal fluids and the kinds of equipment that would be suitable for generating the electricity.

Loose: Several American firms and one Canadian firm had discussed commercial development of geothermal energy with the St. Lucian government. We were not

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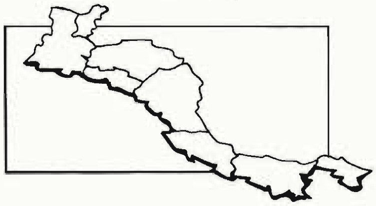


Energy Supply and Demand

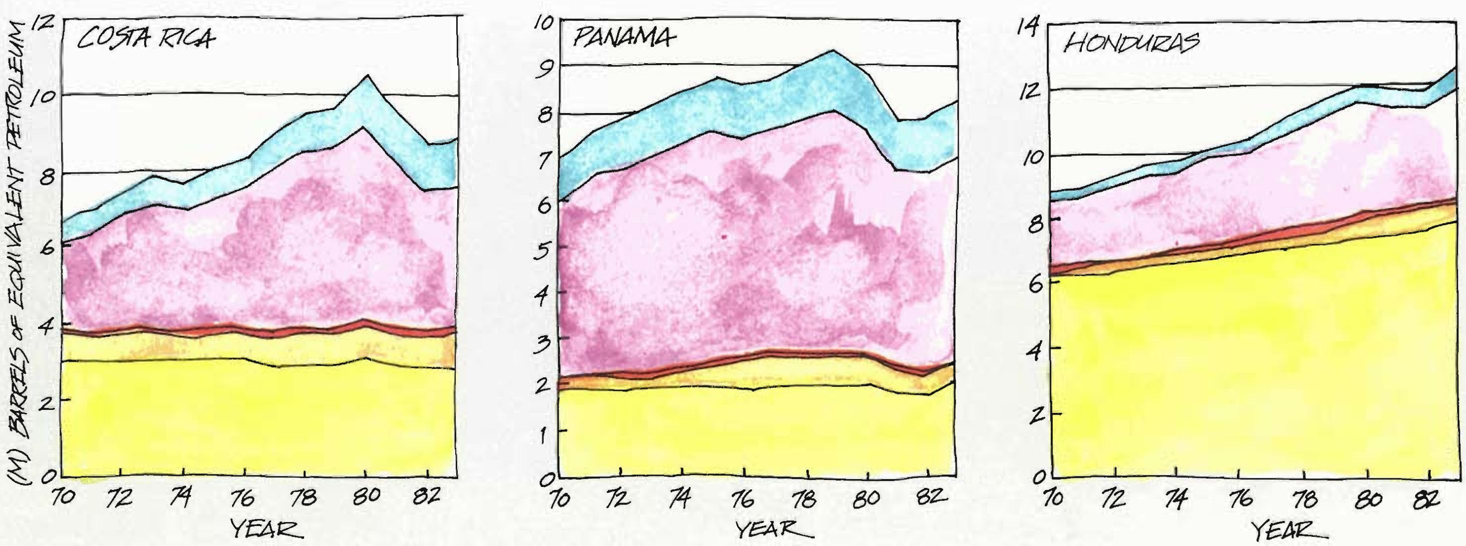
Like those of most developing countries, the Central American economies are dualistic in nature: the rural sector produces mainly traditional agricultural goods, while the rapidly growing urban sector is involved in more modern industrial and commercial pursuits. This dualistic nature is reflected in the pattern of energy consumption shown in the accompanying graphs. People in rural areas rely mainly on firewood to satisfy their energy needs, while those in the cities rely more on electricity and oil products. Consequently, countries with greater degrees of urbanization and higher per capita incomes use relatively more oil products and electricity and less fuelwood than the poorer countries. In 1983, for example, Panama and Costa Rica, the countries with the highest per capita incomes, relied on fuelwood for one-quarter to one-third of their energy needs, while the lower-income countries, Honduras, El Salvador, and Guatemala, relied on fuelwood for two-thirds to three-quarters of their energy needs.

(Data on fuelwood consumption in these and other developing countries are generally poor because much fuelwood does not enter commercial markets where its sale and use can be quantified. The apparent sharp increase in Guatemala's fuelwood consumption in 1979 (see graph) stems from a revision in the estimate of fuelwood consumption rather than a real increase in use.)

In all the Central American countries electricity composes a relatively small share of the total energy consumed, but it has shown the most rapid and variable growth in demand since 1970 (between 1970 and 1980 the demand for electricity grew at an average rate of 9 percent per year).

In the early 1980s Central American countries were hard hit by the worldwide recession. Total energy consumption decreased significantly in Costa Rica, El Salvador, and Panama, and the rate of growth in demand decreased in Guatemala and Honduras. These decreases were absorbed mainly in oil product and electricity demand. Unlike 1973, when oil price hikes could be balanced by debt-financed growth, the early 1980s were a time when large national debts and high interest rates made additional loans difficult and costly to obtain. To exacerbate the situation, the prices received for the main export commodities (bananas, coffee, and sugar) had dropped so low that foreign currency to pay for oil imports and to service foreign debts was in short supply. On a per capita basis Costa Rica and Panama are among the most indebted countries in the world.

With the exception of Guatemala, which produces 1.6 million barrels of poor-quality crude oil per year, the Central American countries have no proven oil reserves and must pay a burdensome price to import oil for transportation and, to a lesser extent, for industry. They all rely heavily on fuelwood, but this resource is threatened in some countries by growing deforestation due mainly to clearing of land for agricultural purposes. By the year 2000 they will undoubtedly face fuelwood



in Central America

by Linda K. Trocki and Steven R. Booth

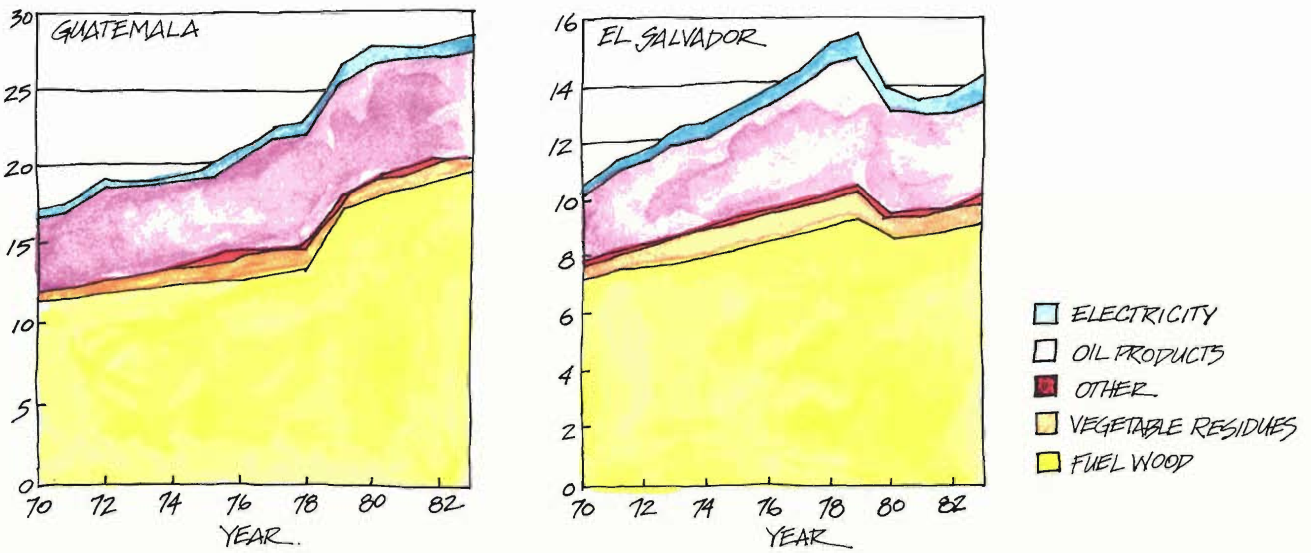
shortages unless substitution or conservation takes place or unless policies to increase fuelwood availability, such as tree farms, are implemented. Since fuelwood is generally gathered by individuals at zero or low cost, finding a similarly inexpensive substitute will represent a major challenge to many of the Central American countries.

The Central Americans can reduce the demand for fuelwood and imported oil by further developing their large potential for hydroelectric energy and geothermal energy, as well as alternatives such as solar energy, crop residues, and peat. As is evident from the graphs, crop residues already play a signficant role in energy supply in most countries in the region. The residues are burned to provide process heat for the food-processing industries and in some cases to generate electricity. In addition, Costa Rica and El Salvador have begun to produce fuel alcohol from sugar cane.

The countries have also lessened their reliance on imported oil by exploiting their hydroelectric resources to generate electricity. The electric generating capacity in the Central American countries ranges from approximately 500 to almost 900 megawatts, and hydroelectric power constitutes more than 50 to 80 percent of this capacity in all the countries. Since 1979 all countries except El Salvador have greatly increased their electric generating capacity by constructing relatively large (250- to 330-megawatt) hydroelectric power plants. However, the Chixoy hydroelectric plant in Guatemala, commissioned in 1983, was down during much of 1984 and 1985 for repair of a tunnel associated with the dam. As a result, Guatemala incurred a large and unexpected requirement for oil-fired generation to meet its electricity needs. (Chixoy recently resumed operation but not at full capacity.) Construction of the large hydroelectric facilities, while reducing reliance on oil imports, has resulted in temporary overcapacity in Costa Rica and Honduras and significant debts to all the national utilities.

The development of indigenous geothermal energy resources represents an attractive alternative to meet the energy demand. Two countries in Central America already exploit geothermal energy for electricity generation—El Salvador and Nicaragua. (The latter is not included in the Los Alamos study.) By 1990 Costa Rica and Guatemala expect to begin generating electric power from geothermal sites now under development.

In summary, Central America, like most developing regions, relies heavily on two forms of energy—imported oil and fuelwood. Continued heavy reliance on these fuels could result in more serious economic repercussions in the future. For example, every dollar spent to pay the oil-import bill precludes the import of a dollar's worth of capital goods that could further production. And the strong market for fuelwood, which has already caused rapid price increases for that energy source, could lead to serious deforestation problems. Conservation and substitution of indigenous resources could ameliorate potential problems. ■



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privy to the discussions that took place, but in the end no agreement was reached. So the United Nations and the AID are paying for the drilling. If geothermal fluid is found, as we expect it will, then the St. Lucia Electric Authority will have to find private money to build the power plants.

Science: *What will your role be during drilling and plant construction?*

Loose: The government of St. Lucia has asked us to serve as consultants as the project proceeds. They have confidence in our advice since we are independent and have no profit motive.

Hanold: Their dealings with private industry will involve areas in which they have very little experience, and they would like Los Alamos to stay and monitor those negotiations.

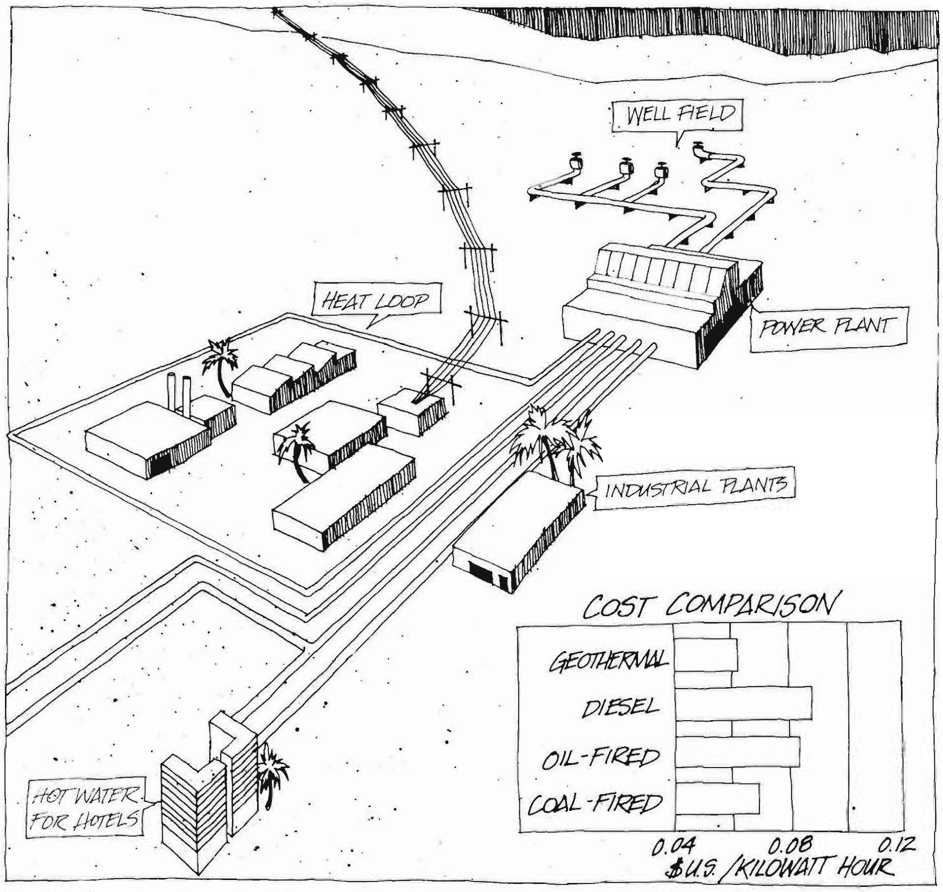
Science: *So you have become ambassadors?*

Hanold: Yes—of good will. The prime minister has shown extraordinary interest in the project. During the six or seven months of field work on the island, we briefed him frequently, and each time he was elated at the progress that was being made. He wants to get a geothermal power plant on line. Several times other organizations have raised the hopes of the St. Lucians for cheap geothermal power and then dashed those hopes by pulling out.

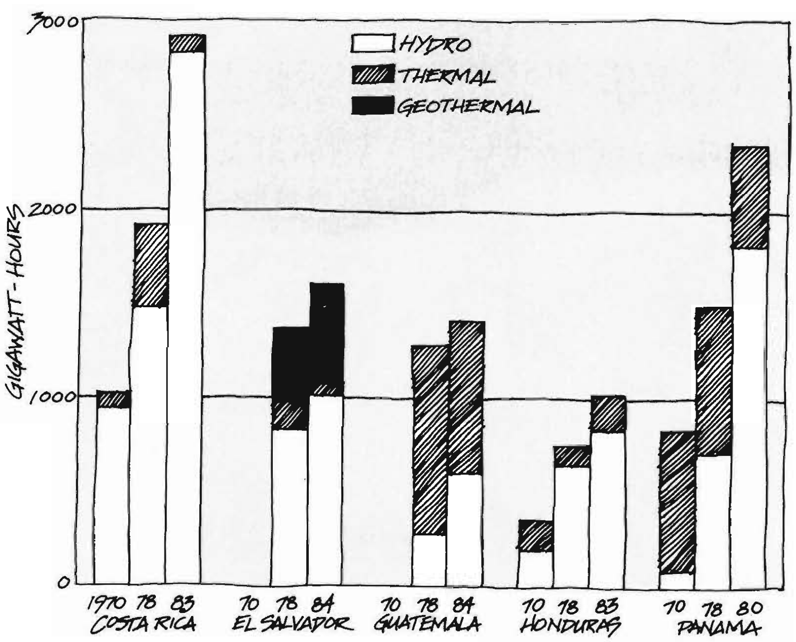
Loose: A geothermal power system would be a secure, low-cost source of electricity, and it could be expanded as the demand for electricity grew. This capacity would help to attract light to moderate industry and thereby alleviate the chronic unemployment on the island.

Science: *Does Central America have similar problems?*

Loose: In some ways yes. The Central American countries are also struggling with chronic unemployment, low per capita income, and energy-supply problems. [See "Energy Supply and Demand in Central America."] In addition they must deal with rapid population growth, class problems, demographic changes, unequal



Costs of generating electricity by various methods in St. Lucia, as determined by Los Alamos economists. The data show that geothermal energy would be the cheapest source of electric power. Moreover, geothermal reservoirs could be used directly as a source of process heat for local industry and of hot water for tourist hotels.



Total amounts of electricity used in five Central American countries. Since 1970 the major increases have been supplied by recently constructed hydroelectric plants.

A native of St. Lucia examining sulfur deposits at the Sulphur Springs geothermal area, which lies within the Qualibou Caldera near Soufrière.

land distribution, and political instability. Their economies are more complex than those of the Caribbean islands. Their industries have been growing, but they lack the necessary industrial infrastructure and technical know-how for a secure industrial base. Moreover they have relied on loans from foreign countries and imported petroleum to support these industries. The region as a whole has amassed a foreign debt of about $12 billion. In the past our assistance has been directed to the rural population, which lives in very poor conditions. We have poured millions of dollars in this direction with little success in improving the quality of life. It has become apparent that our help should be directed toward strengthening their economies.

Science: *Is geothermal energy likely to be important in Central America as a cheap source of power and a means to reduce oil imports?*

Hanold: Yes. Right now hydroelectric power is the most common form of electric power in Central America. But it will be difficult to increase hydroelectric capacity at the rate at which we expect the demand to increase. Hydroelectric plants are very expensive to build. A large plant costs over half a billion dollars, and it is becoming increasingly difficult for Central American countries to borrow that kind of money. Also, two installations in Central America were plagued with technical difficulties that led to cost overruns and reductions in power output. For example, at a new plant in Guatemala, the tunnels that carry the water to the turbines are collapsing because the geologic formations the tunnels pass through are unstable. We have technical problems with dams in this country too. Some of the problems are beyond human control. For example, clearing a valley for a reservoir causes erosion, and the access roads to the plant make it easier for people to cut down trees in the watershed. The deforestation that may result causes more erosion and silting in the reservoir, which, in turn, shortens the useful life of the facility, sometimes dramatically.

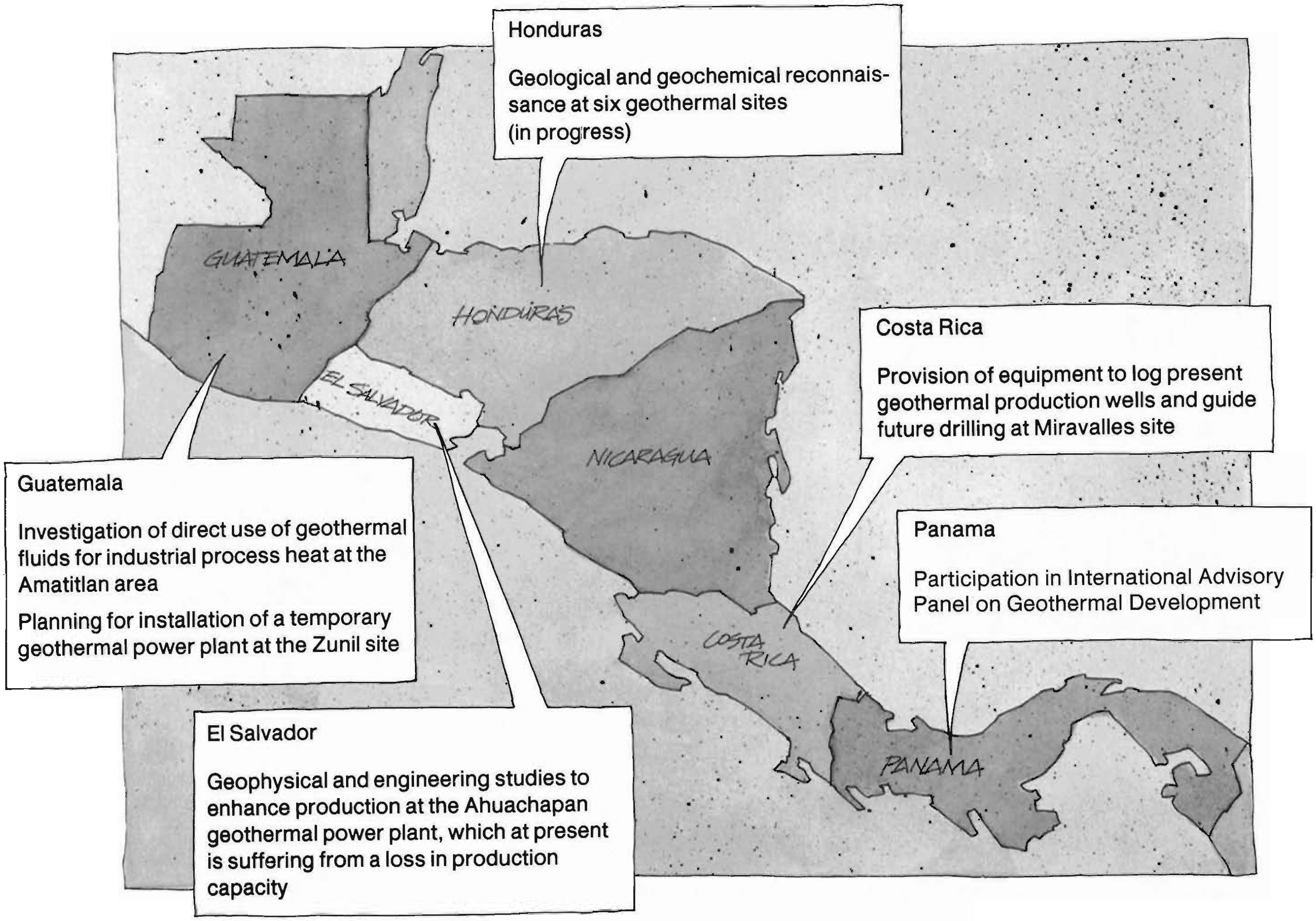
Loose: In our review of the available energy technologies in Central America, we found that Nicaragua and El Salvador had been generating substantial amounts of electricity from geothermal energy. El Salvador was generating over 40 percent of its power from a single geothermal plant called Ahuachapan. That plant has played an important role in the development of the country.

Science: *Where does imported petroleum fit into the picture?*

Hanold: Imported petroleum is needed for industrial and commercial uses and to fuel emergency power plants, the so-called thermal plants that come on line when demand is very high or when problems arise with the hydroelectric plants. One unavoidable problem is the dramatic decrease, by a factor of over a thousand, of the flow rates in the rivers from the wet to the dry season. Many of their plants are so-called run-of-river plants that can operate only when the water is flowing. During the dry season, when the flow ceases, they shut down.

Science: *So is geothermal power very appealing to the Central Americans?*

Hanold: It is ideally suited. The region has tremendous geothermal resources, as evidenced by the volcanic activity that extends from Mexico to the northern part of Panama. The experience of Nicaragua and El Salvador with the Momotombo and Ahuachapan geothermal plants and the recent drilling of successful geothermal wells in Guatemala and Costa Rica make it clear that almost all of the Central American countries can cash in on this indigenous resource. In addition, experience with the Ahuachapan plant makes it clear that the power can be very inexpensive. We are involved in geothermal development in all five countries mentioned earlier, but since Honduras lies



Roles played by Los Alamos scientists in the development of geothermal energy in Central America. Need and stage of development dictate the extent and nature of the support.

slightly outside the volcanic belt, defining the nature of its geothermal resources has provided us with the most challenging project in the area. We are now getting the field data back, and early indications are encouraging. The Honduran geothermal sites are not the typical volcanic variety found in El Salvador or Costa Rica but the Basin and Range type prevalent in the western United States. The Hondurans expect to reach a hydropower shortfall by 1993 and need to know by 1988 whether geothermal development can provide an alternative source of power. We still have a lot of work to do before we can assure them of the success of geothermal development. [See "Geology of Honduran Geothermal Sites" and "Geochemistry at Honduran Geothermal Sites."]

Science: *Tell us something about your personal reactions to working in Central America. For example, how do you feel about working in countries where the political situation is volatile?*

Hanold: It is not without strain, but we're getting used to it. When I first went to El Salvador, I was rather disconcerted by the presence of armed guards at the entrances to the offices of many government organizations. The directors of these organizations are usually political appointees, and one can't help but be aware that their personal safety may be at risk. Even our technical colleagues in these countries are not immune from political difficulties. All these things are upsetting at first. But the Central Americans are so pleasant to work with, so enthusiastic about our presence, and so appreciative of our help that I really look forward to the trips. The political atmosphere is just a fact of life; it's not ideal, but it doesn't prevent our doing an important job for these people.

Loose: And the Central Americans see our job as very important. Our activities are given a big play in the national presses. Even a series of lectures by Los Alamos scientists is accompanied by a great deal of fanfare and publicity. Sometimes the respect they give us is a little bit embarrassing because our technical opinions carry so much more weight with the local authorities than those of their own technical people. Fortunately, this does not seem to cause jealousy or ill feelings. On the contrary, our relationships with their technically trained people have been the most satisfying aspect of the entire project. They watch our people work in the field, they see them get their hands dirty, they see them work long hours with little supervision, and they admire what they see. Our ease of getting things done is surprising to them because they would require many levels of supervision and intricate advanced planning to accomplish similar tasks.

Science: *Are the Central Americans at all wary of your presence because of past experiences?*

Loose: Wariness is an appropriate word because they have been disappointed in the past. Some projects by foreign investors never get finished. We are working to build a strong relationship with these countries, not in the political sphere but rather through one-on-one relationships with the technical people of the country. By conveying a true image of American professionals, we are gaining trust.

Science: *In terms of the politics, does the State Department help you?*

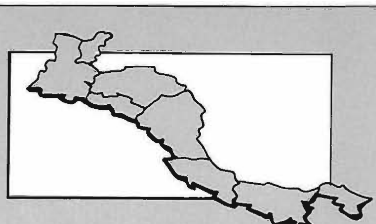
Hanold: Yes, through the AID. Normally our first stop in a country is at the AID mission office. We brief them on the purpose of our trip, and they give us an up-to-the-minute report on the country, advising us about any tense situations and any regions of the country that we should avoid. As we are leaving the country, we give the mission office a report about what was done during the trip and how successful it was.

Loose: The AID missions have been very helpful because they have a corporate memory of the country's history and an extensive network of contacts. Many of the AID people speak fluent Spanish. Most important, they have a finger on the pulse of the country. They are able to give us reliable information on how to get the job done and on which people and organizations are likely to be effective.

Hanold: They are also very helpful with more mundane things, such as providing transportation and meeting us at the airport on late-night flights and seeing that we get to our hotel safely. Many of our field operations take place in very, very remote areas, and the field crews may come through a city only every five or six days. The AID mission has our itinerary and knows the people involved. If a problem were to arise, we feel confident that they would take it upon themselves to go out after our people.

Loose: The AID and Los Alamos have one aim in common—to see that when something is started, it is finished. We have an effective working relationship with the AID, and it is improving daily.

Hanold: In technical areas we act as a filter for the AID. We hear requests from local experts for training or for equipment, and we separate the technically less important requests from those that have merit. We submit to the AID the proposals that we think will have the greatest economic impact on the country. From the beginning our intention has been to involve people from the host countries in all stages of the



The Costa Rican Peat Project

by Gary R. Thayer, K. D. Williamson, Jr., and Arthur D. Cohen

Scientists from the Laboratory and Refinadora Costarricense de Petróleo (RECOPE) are working together to assess the development potential of peat, an indigenous, unused resource in Costa Rica. This carbon-rich organic sediment, produced in swamps and marshes from partially decayed organic matter, could become a significant asset in a number of different ways. If made into briquettes and used as a fuel for heating and cooking, it could help reduce the heavy dependence on fuelwood, which now supplies 50 percent of Costa Rica's energy. If used to fuel electric power plants, it could help reduce oil imports. Since harvesting of peat is a labor-intensive operation, its development would provide jobs for the people in the areas where it is found. Further, its availability as a fuel might bring industries to those areas. Eventually peat might become the basis of "high-tech" industries converting this resource into liquid and gaseous fuels or valuable organic chemicals such as waxes, resins, and medicinals.

Despite all this promise and the extensive literature documenting the wide and growing use of peat in northern Europe, Ireland, and the Soviet Union, the development of peat in Costa Rica entails facing many unknowns regarding harvesting methods, appropriate and acceptable end uses, and overall economic impact.

So far we have surveyed the literature on harvesting and end uses and have made projects, including planning. Even for our original proposal to the AID, we solicited their opinions concerning their biggest energy- and mineral-related problems. And then we tried to address those problems squarely in the proposal.

Loose: We worked with geologists, engineers, economists, and fairly senior administrators of both utilities and government organizations such as ministries of energy and mines.

Science: *Had they had much contact with Americans before?*

Hanold: Yes. Since many Central American schools do not offer advanced degrees, many technical people have pursued such degrees in the United States. As a result most of our Central American counterparts speak English very well.

Loose: The AID regards education as a basic human need. In addition to their program of education at the primary and secondary levels, they help people with university potential to get an appropriate education at American universities.

Hanold: The local culture and pride are such that they don't want someone just coming down, doing a job, and walking away. They appreciate the assistance but want to participate in the doing. They want to be involved technically and physically. In all our interactions we stress working with the people in the region. We have the techniques to do certain tasks, and through our work they get exposed to the cutting edge of geology, volcanology, geochemistry, and geophysics. That experience will be left behind. In some cases we are actually leaving equipment behind so that they can continue on their own.

Loose: The people are very nationalistic and very proud of their countries. They have definite ideas on how to use the new knowledge we are giving them. A concrete example is the peat project in Costa Rica. We were very interested in the possibility of briquetting the peat for use as a cooking fuel in place of wood. It was a way to save the fast-disappearing forests. The national oil refinery, whose charter is to promote high-tech industry, was initially more interested in using the peat to produce petrochemicals, waxes, and resins and to generate electricity. Through discussion we have reached a mutual agreement to investigate both high- and low-tech uses of peat. That gives you an idea of how the input of local people is reflected in the projects. [See "The Costa Rican Peat Project."]

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a preliminary field assessment of Costa Rica's peat resources. Two moderate-size peat bogs have been identified. Other sites exist but have yet to be explored. One identified site is in a sparsely populated region on the Nicaraguan border whose settlement would promote Costa Rica's national security. The other is a jungle site near the Caribbean coast. Both sites are large enough to provide fuel for a 10-megawatt electric power plant for 100 years or more. One of these locations may be chosen as the site for a demonstration peat project.

Peat, in its natural state, contains up to 95 percent water and must be dried to a water content of 50 percent or less before it can be burned. In Europe solar drying is used almost exclusively to reduce the water content. Milled peat is produced by draining the top few centimeters of a peat bog, scraping off the exposed layer, allowing the sawdust-like product to dry in the sun for a day to a week, and then collecting it with rakes or large vacuum cleaners. Sod peat is produced either by cutting out

A view of the flora characteristic of the peat site located in a tropical jungle region of Costa Rica near the Caribbean coast. The peat deposit here is extraordinarily thick, at least 12 meters. In the center of the photograph is a species of palm that is often associated with peat deposits.

Science: *What difficulties do you face in carrying out your work?*

Loose: Coordination, communication, and logistics are among our biggest difficulties. We have Washington looking over our shoulders as well as the local AID missions. In addition, we maintain contacts with government people in the five countries. The wide range of the projects, which include economic analysis, mineral exploration, and development of geothermal power, compounds our difficulties.

Hanold: Another difficulty is that sometimes the technology involved in a project is unfamiliar to the people in the host country, and they find it hard to understand how the project will get from A to Z. For instance, a geothermal energy project starts with geologists mapping the area and geochemists collecting water and gas samples from hot springs. These activities may seem mystifying. What do hot water samples have to do with electricity on line? To lessen this problem, we recently took two Honduran visitors to an operating geothermal power plant in the United States. These gentlemen were from the national organization that generates much of the electricity in Honduras, mostly from hydropower. They were at Los Alamos to help make long-range plans for a geothermal project in their country, and we spent a day at the Geysers plant in northern California as preparation. The Geysers, the largest geothermal power plant in the world, supplies much of the power for San Francisco. We took them up on drilling rigs, showed them how the wells are drilled, talked about the site's geology, geochemistry, and geophysics, and showed them how the geothermal steam is extracted, collected, and run through turbines at the power plant. The tour gave them a concrete understanding of the whole technology. I think many of our projects will require a similar educational effort.

Science: *Are you in contact with the rural populations of the Central American countries?*

Hanold: Very much so, particularly during our geothermal work in the remote areas of Honduras and our explorations for minerals in very remote areas of Costa Rica. Since these areas have no conventional hotels, arrangements are made with local people for sleeping accommodations and food. We usually hire someone local to buy and cook food for the field parties

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blocks of peat by hand and stacking them to be dried or by cutting sections of peat by machine, grinding the peat, and extruding it in 2- to 10-centimeter-diameter cylinders. These "sods" are allowed to dry and then collected. Since both methods involve a solar drying step, they may be impractical at the two Costa Rican sites, which receive between 3 and 5 meters of rain per year. Instead, the peat may have to be dried artificially. Alternatively it can be collected in a slurry and heated to about 200°C to initiate exothermic oxidation reactions that produce free carbon, which can be collected and compressed into a coal-like substance, or, if the oxidation is carried to completion, heat for industrial use. Such wet harvesting methods are generally more expensive than the traditional methods described earlier, so their use in Costa Rica will make the economics of peat development different from that documented in the literature.

The environmental impact of peat harvesting and the economics of various end uses are also being examined. Mining of peat results either in changed drainage patterns or lake formation, both of which can be beneficial. Changed drainage patterns might permit reclamation of the mined areas as prime farm land, or the lakes could, according to a study done in Jamaica, be used for aquaculture.

Appropriate end uses for peat depend, first of all, on the quality and size of the resource. The higher ash content of presently known Costa Rican peat versus European peat may affect production technology and costs as well as quality of the end products. This possibility needs to be investigated. We are hopeful that the Costa Rican peat will be suitable as a fuel for electric power plants. Although these plants will be smaller in scale than typical European plants and the cost per unit output will therefore be higher, the additional cost might be offset by reduction in oil imports. We are most excited about the use of peat as a cooking fuel in place of wood, but the local population may not be equally enthusiastic, especially in areas where wood is plentiful and free for the gathering. The Costa Ricans are particularly interested in high-tech uses, such as the production of gaseous fuels and organic chemicals, but these may be too ambitious technologically for a first attempt at using the resource.

We and our Costa Rican colleagues are gathering information relevant to all these issues. We will also test the performance of peat in local cooking stoves and in larger scale combustion and gasification applications. The results, plus detailed information on specific peat sites, economics of harvesting, environmental effects, potential for reduction of oil imports, and development of remote areas, will be used to choose a demonstration peat project. We, as well as the Costa Ricans, look forward to finding a way to make this resource an economic success. ■

and to provide some structure, even an empty house, for sleeping. It is definitely not a downtown Marriott.

Science: *Are geothermal sites part of the culture of the people?*

Hanold: In the more primitive parts of Honduras, people use the hot water for simple needs such as sterilizing baby bottles, boiling eggs for lunch or cooking chickens for dinner. Information on the locations of many hot springs has come from the natives. They'll watch from a distance and then approach us and indicate that if we like that hot spring so well, they know of another one over there. We always make sure that at least one member of the field team speaks Spanish fluently so that communication is always possible.

Science: *The interactions must be quite different from those you have been accustomed to in this country.*

Hanold: Very definitely. Through the DOE we have been technically involved in many geothermal energy programs with American industries. Our experiences in Central America have a very different flavor. The people are exuberant and naturally inquisitive. After working in the field with our people, they ask question after question about what we did and why we did it. So we are training them as we go.

Science: *Which Laboratory divisions are involved in the project?*

Hanold: Geologists, volcanologists, and geochemists from the Laboratory's Earth and Space Sciences Division are doing the geothermal reconnaissance in Honduras and Costa Rica and the mineral exploration in Costa Rica. Some of our people have been in the field almost every month since the project started. These people have a great deal of experience with geothermal systems in the Rocky Mountain region of the United States and throughout the world—Europe, Asia, and St. Lucia. Soon engineers will be needed to log the geothermal wells, that is, to measure the temperature, pressure, and flow rate of the fluids in the wells and determine the nature of the rock formations in the reservoir. Central America has almost no equipment for logging hot wells. The measurements in Costa Rica, Guatemala, and El Salvador will be made with special equipment developed at Los Alamos to function in the high-temperature—up to 240 degrees Centigrade—environment of geothermal reservoirs. [See "High-Temperature Borehole Measurements at Miravalles, Costa Rica."]

Loose: Economists and energy technologists from the Laboratory's Systems Analysis and Assessment Division are also heavily involved in the project. All told, between sixty and seventy people from throughout the Laboratory contribute directly, but that number does not include the many people who provide support, such as working on publications, purchasing equipment, and arranging travel. These people have been very helpful about expediting or bending the Laboratory's procedures to get the job done.

Hanold: The project would rapidly grind to a halt if we followed all the conventional foreign travel rules. Thanks to the Travel Office staff, the approval time for foreign travel has been reduced from sixty days to two hours. They really deserve a pat on the back for accommodating our people.

Loose: So do the people who process our purchasing contracts in record time. We do other unorthodox things, such as hiring Central Americans as consultants and paying for local management offices. The Laboratory does not normally do business that way.

Hanold: We have many logistics problems. Our field people are only now getting access to places to store their gear in the host countries so they don't have to bring it back after each field trip. We had to arrange special assistance from the host countries to get equipment and samples through customs into the host countries and samples back to Los Alamos for analysis.

Science: *What types of equipment do you send down?*

Hanold: To sample the springs in Honduras, for example, we needed thermometers, pH meters, conductivity meters, and bottles for shipping samples back to the Laboratory for further analysis.When we start the geophysical studies and well logging, we will bring in very large pieces of equipment—high-voltage power supplies, diesel generators, a logging truck, and so on. The logging truck is equipped with a spool of special cable about 10,000 feet long, a data-acquisition system, a computer for data processing, and its own power supply. The cable is used to lower various tools into the well and to transmit signals from those tools back to the data-acquisition system in the truck. One can collect real-time data on what is taking place in the well with this self-contained truck. A similar setup is used at the Laboratory's Fenton Hill hot dry rock geothermal site near Los Alamos and at various locations in Nevada and California. We may have some trouble getting this equipment and the drilling rigs into some of the remote sites in Central America. So far we have needed only small four-wheel-drive vehicles and have had no trouble, but we have yet to experience a full rainy season.

Science: *How much money is dedicated to the project?*

Loose: During this first year and a half we have $10.2 million, but in charting our course for the next five years, we see the costs increasing to about $15 million annually by 1986. So the project represents a substantial effort for the Laboratory and for Central America. A fair fraction of the funds will be spent on salaries of the core group of between thirty and forty Los Alamos people who work on the project.

Hanold: The remainder will be spent on goods and services. We are fabricating and buying equipment that will be left behind in Central America for use throughout the region. Since we will also be renting equipment from Central American countries to drill shallow wells, a fair portion of the money will be spent in the host countries.

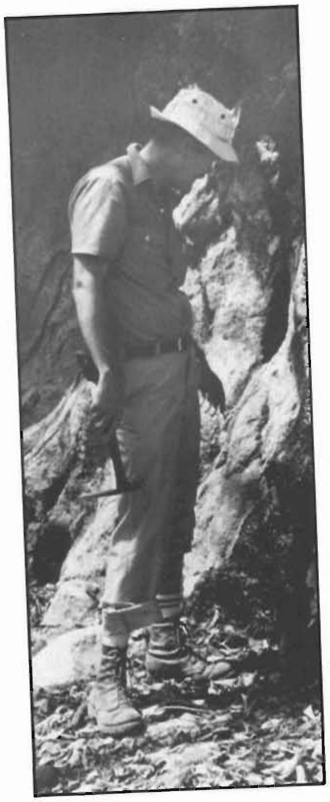
Loose: A significant portion of the total will go to the U.S. Geological Survey, who

Wilfred Gutierrez standing next to a boiling spring at Platanares, Honduras. Note the white deposits of silica sinter, an indication of subsurface reservoir temperatures equal to or greater than 150°C. (Photo by Fraser Goff.)

will participate in the mineral and geothermal work. Consultants, universities, and other organizations will also participate and receive a portion of the funds.
Hanold: One of the exciting parts of the project is the opportunity to sponsor graduate students. Central Americans who are capable of doing excellent research but have been unable to get funding will be supported to do research in their countries. I think this aspect of the project will prove to be one of its biggest successes.
Science: *Let's talk in a little more detail about the technical work. What do the economists do?*
Loose: We have had teams in all of the countries except El Salvador. They interact with the economic ministries and energy-planning ministries to collect data on energy consumption, energy production, and energy resources. This information will be used as a database for analyses—with small computers we will provide—to determine directions for energy development. The economists here at the Laboratory have a lot of experience with such analyses for our own country, which is asking the same question. How can our petroleum imports be reduced? In the case of the geothermal projects, our economists work with the local economists and energy planners to help characterize the available energy options. In St. Lucia, for example, we compared the costs of producing electricity by various methods and the impacts of these methods on the overall economy and on petroleum imports. The St. Lucians asked for these cost comparisons, and our analysis was based on the information provided by Los Alamos geologists and engineers. We also looked at the macroeconomy of the country to forecast the growth in energy demand and to determine the energy capacity that should be installed to meet that demand.
Science: *Bob, would you outline the geothermal work?*
Hanold: A geothermal power system requires a hot fluid, usually called brine, that consists mainly of mineralized water and steam. The temperature of the brine should be at least 180 degrees Centrigrade to generate electricity efficiently. The rock containing the fluid must be well fractured or porous, since fluid tightly trapped in impermeable rock cannot be accessed. In Honduras we began the search for suitable geothermal reservoirs by studying in greater detail the geology of six areas where high-temperature springs were known to exist. Then we sent a geochemistry team to collect and analyze samples of the surface waters and predict the temperatures of the underground reservoirs. Over the last ten or fifteen years geochemists have developed empirical correlations between the properties of surface fluids and the temperatures of underground reservoirs. This area of geochemistry is called geothermometry. Our geochemists have a great deal of experience with geothermometric techniques, which worked very well as predictive tools in St. Lucia.

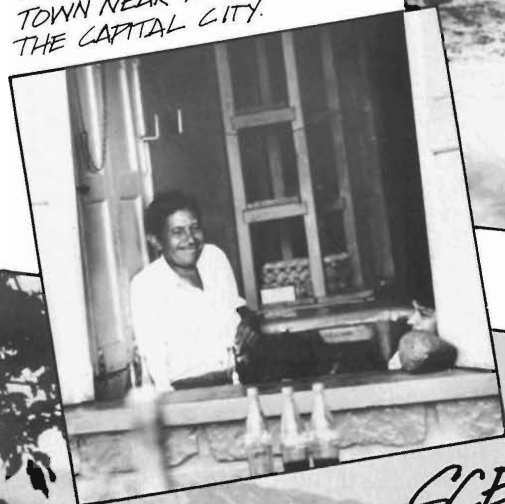
One of the best known geothermometric techniques is use of the sodium-potassium-calcium geothermometer, which provides an estimate of the temperature of a reservoir from the relative abundances of those elements in the surface fluids. According to this geothermometer, the reservoir temperatures at two Honduran sites, Platanares and San Ignacio, are well above the 180 degrees required.

SCENES FROM HONDURAS



GRANT HEIKEN EXAMINING PADRE MIGUEL IGNIMBRITES AT THE PLATANARES GEOTHERMAL SITE.

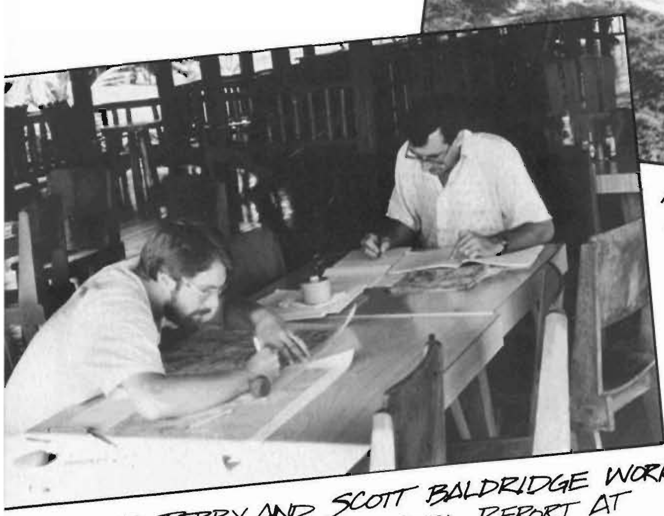
HONDURAN IN A RESTAURANT IN SUYAPA, A SMALL TOWN NEAR TEGUCIGALPA, THE CAPITAL CITY.



LA MASICA HOT SPRINGS, SAMBO CREEK GEOTHERMAL SITE.

REGION NEAR THE PAVANA GEOTHERMAL SITE.

LITTLE GIRL IN AZACUALPA.

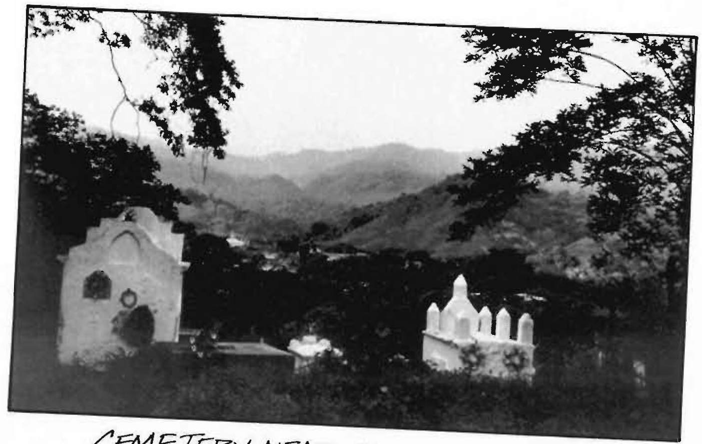


FRANK PERRY AND SCOTT BALDRIDGE WORKING ON THE AZACUALPA TECHNICAL REPORT AT LAGO DE YOJOA.

FARM ANIMALS NEAR THE SAMBO CREEK GEOTHERMAL SITE. HONDURAS HAS A BURGEONING BEEF INDUSTRY, AND STEAK IS OFTEN THE CHEAPEST MEAL ON THE MENU.

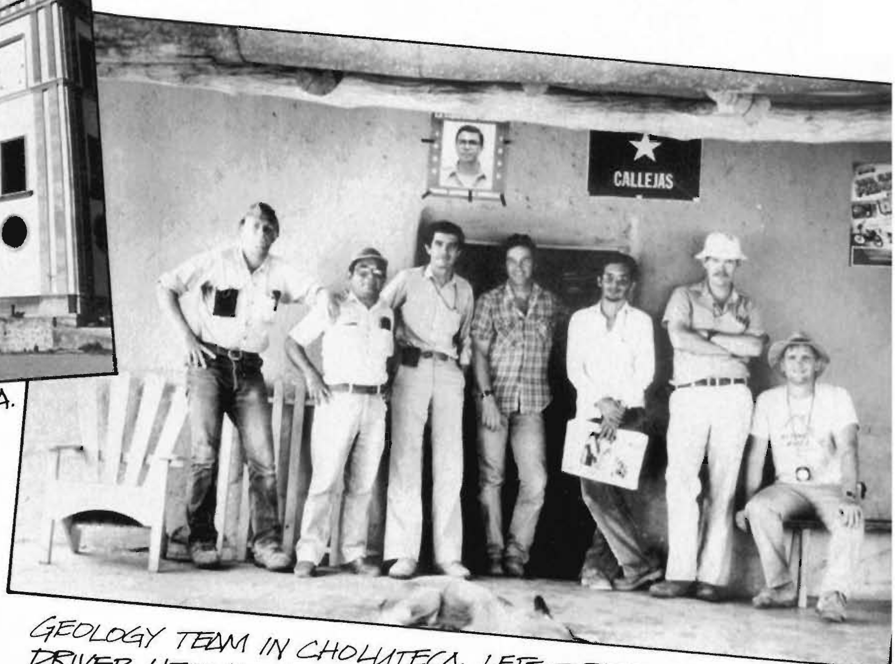
HONDURANS IN A LOCAL STORE, SAN FRANCISCO DE OJVERA.

GIRLS CARRYING WATER FROM A WELL NORTH OF EJOC.

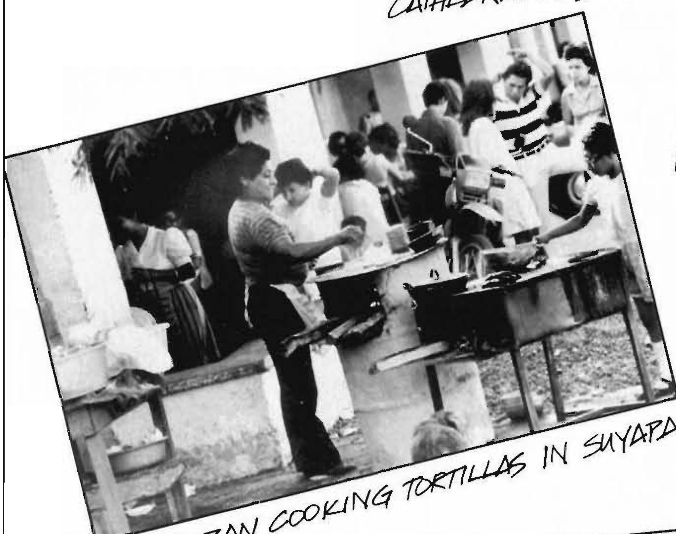


CEMETERY NEAR SAN PEDRO ZALAPA.

CATHEDRAL AT SUYAPA.



GEOLOGY TEAM IN CHOLUTECA. LEFT TO RIGHT, DEAN EPPLER, DRIVER HERMAN, WILMER FLORES, WENDELL DUFFIELD, RODRIGO PAREDES, GRANT HEIKEN, KEN WOHLETZ.



HONDURAN COOKING TORTILLAS IN SUYAPA.

DEAN EPPLER PASSING OUT POLAROID PRINTS TO CHILDREN IN AZACUALPA.

CAMPESINOS NEAR SAN FRANCISCO DE OJUERA.

Some participants in the Caribbean Basin Proyecto. Front row, left to right: Ken Wohletz, Tony Montoya, Flavio Gurule, Ron Lohrding. Middle row, left to right: Steve Bolivar, Gary Thayer, John Altseimer, Gloria Bennett, Anne Tellier, Bob Hanold, Annette Turpin, Dean Eppler, Pat Aragon, Bill Laughlin. Back row, left to right: Joe Frank, Duane Marr, Fred Edeskuty, Grant Heiken, Ken Williamson.

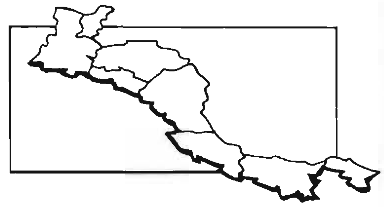
Other data corroborate these measurements, so our confidence in the geothermal potential of Honduras is growing. [See "Geochemistry at Honduran Geothermal Sites."]

We also determine a gas geothermometer temperature from the relative abundances of various gases in the surface fluids. These gases are either dissolved in the fluid or are contained in the steam that reaches the surface through a fumarole, a steam vent. Geologic data, such as rock composition and age and the geologic history of the site, are also valuable in geothermal exploration. For instance, magma, molten lava, is usually closer to the surface in younger geologic systems. So geothermal reservoirs in younger systems are easier to develop because higher temperature fluids occur at shallower depths. We have come to understand that, in Honduras, the high temperature gradients near the surface are due to thinning of the earth's crust by tectonic processes. [See "Geology of Honduran Geothermal Sites."]

We also send our geophysicists to some sites to perform electrical measurements. With a high-voltage generator they establish an electric field in the ground, and then with probes they measure the electric field at various distances from the source. If the ground had a constant resistivity, the field would vary with distance in a certain way. Any perturbations on that variation reflect changes in resistivity, which in turn indicate the presence, for example, of fluid-filled faults and fractures. From the data the geophysicists can determine the locations, both horizontally and vertically, at which such features occur. This information tells us about the plumbing of the reservoir. However, since the electrical measurements are time-consuming and expensive, we limit them to only those sites with the most promising geologic and geochemical properties.

Science: *Over how big an area are the electrical resistivity measurements made?*

Hanold: In St. Lucia we ran a 5-kilometer-long resistivity survey cable through steep,



wet, dense jungle. The entire trail had to be cut with machetes. We also measure temperature gradients by drilling holes with fairly small diameters to a depth of 300 to 500 meters. The higher the temperature gradient is, the more promising the site is. After all this information is collected and analyzed, we pick locations to drill the production wells. In St. Lucia we picked three locations along the 5-kilometer resistivity line.

Science: *Does the fluid have to be pumped out of the reservoir?*

Hanold: Fortunately, pumping is unnecessary for most high-temperature geothermal reservoirs. The fluid boils as it rises in the well, and the emerging steam lifts the fluid by lowering its density.

Science: *Does a geothermal reservoir cool off as it is used?*

Hanold: Not by very much. It can lose its pressure but only gradually and after long production. Some reservoirs are very large, extending vertically for 2000 to 3000 feet and horizontally for miles. The rock is essentially saturated with brine. Much of the fluid that reaches the surface through the well is injected back into the earth and is reheated as it percolates through the hot rock.

Science: *Will the economist summarize the point of the project?*

Loose: If oil were still $1.50 a barrel, we wouldn't be carrying out this project. Economics provides the rationale for our helping these countries identify and develop their indigenous energy resources. If oil were still cheap, the best thing we could do would be to continue to burn oil.

Hanold: I'd like to say a little more about the people and the cultures we've encountered. The Central Americans are very adaptable and jump at the chance to learn new techniques. They are very eager and aggressive. If they take a short technical course, they want a diploma to verify their training because it may have an impact on getting a promotion or a raise. So we plan to grant diplomas for a course, now being developed, on conducting field work for geothermal reconnaissance.

Loose: In the Latin way of doing business, the bosses have a great deal of power, more than we are used to, and command the respect of the people who work for them. Respect for authority is very much a part of their culture. As a consequence, you have to deal with organizations at the appropriate level of authority. If you go too low, the person can't help you. If you go too high, you have made a faux pas. You have to understand and work within the hierarchy.

Science: *Does the style of communication differ from ours? When you want to get something done, can you be direct about it?*

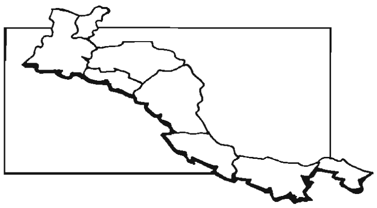
Hanold: We have been very direct. Meetings follow a pattern similar to ours, and it has certainly been my experience that we can deal around a conference table with the Central Americans much as we would with our fellow citizens.

Science: *What is the outlook for this project?*

Loose: We have been working in Central America for seven months and are now beginning to see more clearly both the obstacles and the promise. The initial euphoria of getting funding and the novelty of working in exotic places is being replaced by the real difficulties of implementing this multicultural, multipurpose project. We are learning that good intentions are not enough. Communication among the various arms of the project across thousands of miles and between cultures requires management skills beyond those normally required. We need to do more detailed planning and closer monitoring to avoid misunderstandings. On the other hand, we are more certain than ever that the project can have a significant impact. The peat work is particularly exciting because it may lead to a brand new technology in Central America. The geothermal work is very important because it may result in reduced oil imports and foreign debts. It will take tremendous dedication and perseverance to realize the goals of the project, but we and our Central American friends are up to the challenge. ■

Geothermal Projects

- **Geology in Honduras**
- **Geochemistry in Honduras**
- **Borehole Measurements in Costa Rica**



Geology of Honduran Geothermal Sites

by Dean B. Eppler

Since March 1985 a team of Laboratory geologists has been working with counterparts from the Empresa Nacional de Energía Eléctrica (ENEE) of Honduras and from four American institutions on a project to locate, evaluate, and develop geothermal resources in Honduras. The team, headed by Grant Heiken and funded by the U.S. Agency for International Development, has so far completed three trips to Central America to study in detail the geology of six geothermal spring sites.

Basic Geology of Honduras

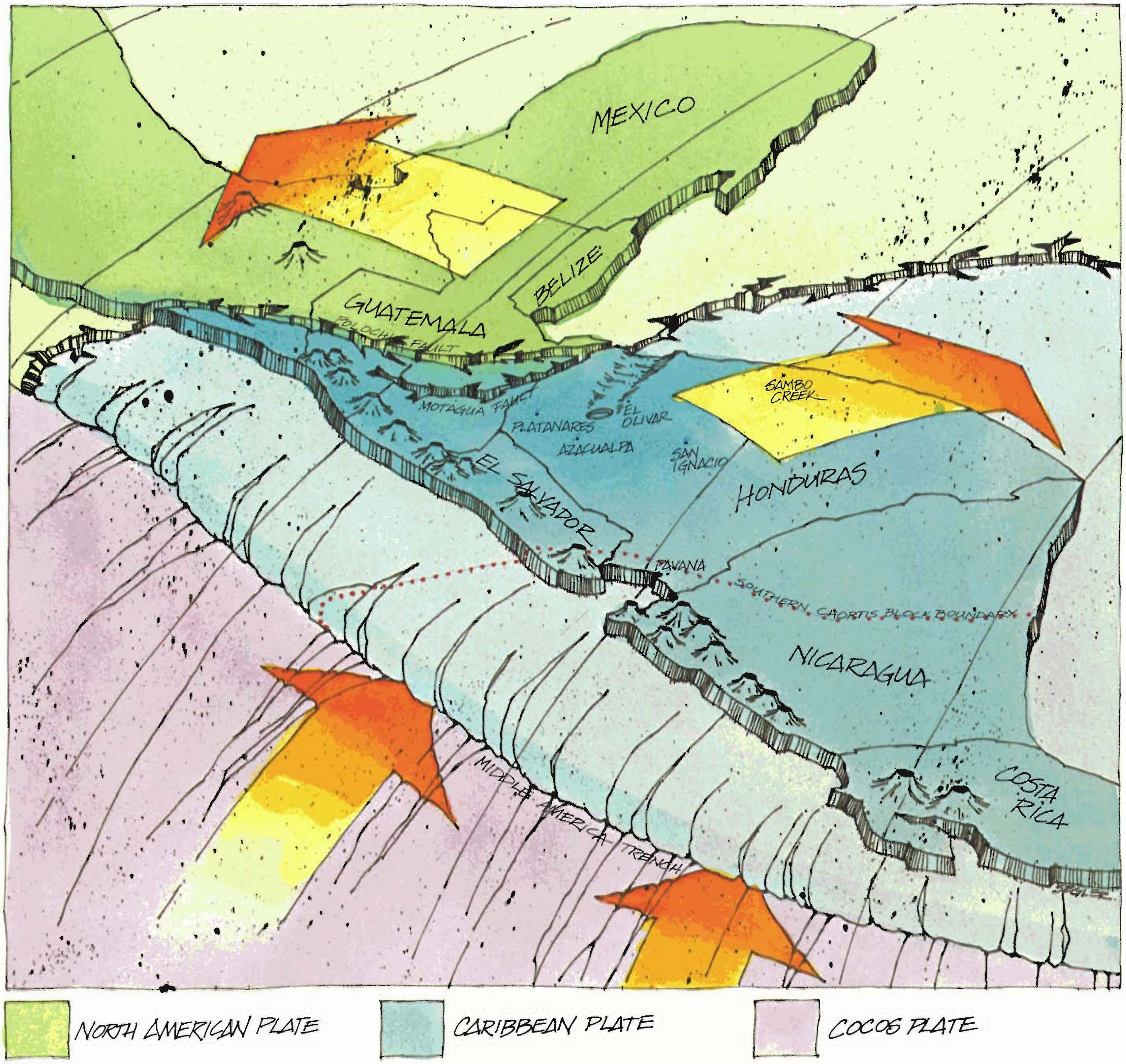
Honduras, the largest and most rugged country in Central America, is perhaps the least known geologically. Its steep terrain, dense vegetation, and paucity of roads hampered basic geologic studies until the late 1960s. Since then studies sponsored by American universities, including Ph.D. dissertations by project collaborators Bob Fakundiny and Rick Finch, have meshed with a greater level of in-country expertise to produce a basic understanding of the geology of the country. Such an understanding is an essential first step in any geothermal exploration. It has been particularly useful in Honduras as we set out to determine the nature of the geothermal heat source and the "plumbing system" through which the geothermal waters reach the surface.

The geology of Central America is extremely complex. The meeting of three tectonic plates in western Guatemala and southern Mexico has resulted in an unusual juxtaposition of structures and rock types whose geologic history has yet to be unraveled. Textbook reconstructions of tectonic-plate motions very often sidestep the problem of how Central America developed through geologic time by never showing its existence until the present time.

As shown on the accompanying map, Honduras lies on a portion of the Caribbean tectonic plate called the Chortis Block. This block, composed of rocks deposited in a continental environment, is bounded on the north by large strike-slip faults in sourthern Guatemala (the Matagua and Polochic faults) that form the boundary between the Caribbean plate and the North America plate.

The continental rocks of the Chortis Block are bounded on the south by younger rocks in Nicaragua that were deposited in an oceanic environment. The western boundary of the Chortis Block lies along the Central American volcanic chain and the Middle America Trench, a subduction zone where the Cocos plate is being thrust under the Caribbean plate. The complex geology of Honduras is the result of its proximity to the intersection of the three tectonic plates. In some areas of the country, major faults lie less than 10 meters apart. Most of these are normal faults, developed as a result of stress that is literally pulling the country apart along an east-west axis. Although Honduras has been spared the devastating earthquakes that have rocked much of Central America, we suspect that deformation is taking place continually; in some areas faults cut stream gravels that are only several thousand years old. The result of this faulting, as shown in the accompanying photo, is rugged topography dominated by north-south oriented fault basins and adjacent fault-block mountains very similar to those found in the Basin and Range physiographic province of the western United States.

The rocks of Honduras were deposited in rapidly changing environments, and the resulting stratigraphy is as complex as the structures that modify it. Precise dating is difficult because of the absence of identifiable fossils and the rapid changes in rock types over short geographic distances. However, three distinct age groups are apparent: a basement complex of Paleozoic low-grade metamorphic rocks about 245 million years of age (Horne, Clarke, and Pushkar 1976); an overlying section of Mesozoic limestones and redbeds that is estimated to be between 100 million and 200 million years of age (Mills et al. 1967); and a thick upper sequence of volcanic rocks from two distinct episodes of volcanism. The Matagalpa Formation, a



Honduras is positioned on the Chortis Block near the junction of three tectonic plates: the North American, the Cocos, and the Caribbean. The large arrows indicate the direction of motion of the plates. The Cocos plate is being thrust under the Caribbean plate along the Middle America Trench. The Motagua and Polochic faults are large strike-slip faults separating the North American plate from the Caribbean plate. The plate-tectonic and geologic histories of the area are not known well enough to explain how and when Central America was formed. For example, the southern boundary of the Chortis Block, where continental rocks end and oceanic rocks begin, is indicated by a dashed line because its exact location in the jungles of Nicaragua has not been determined. We do know that plate movements are continuing to create faulting throughout Honduras and pulling the country apart along an east-west axis. Rainwater circulating through the fault regions has created numerous geothermal systems. The map also shows the locations of the six geothermal sites now being evaluated as indigenous sources of energy.

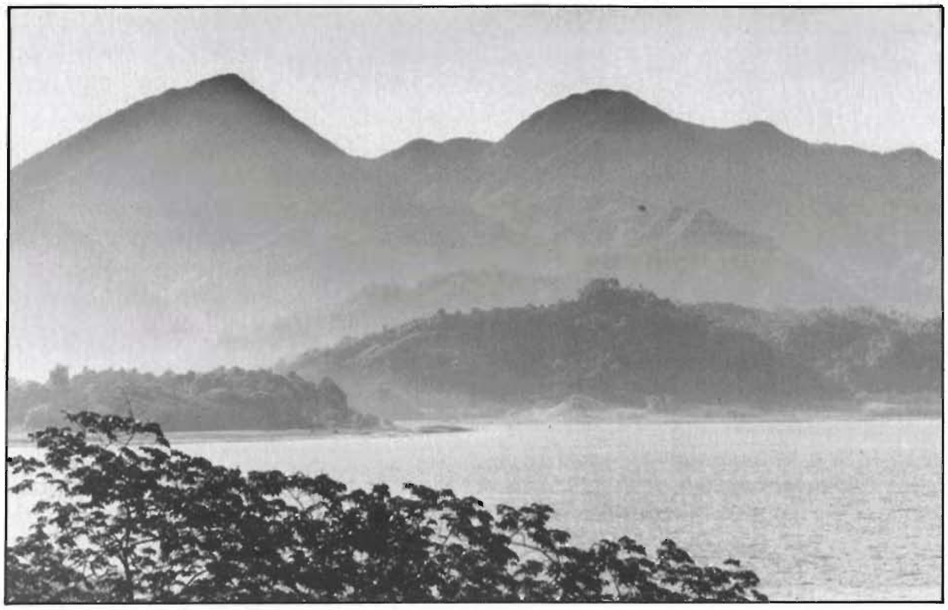
series of early Tertiary interbedded lava flows, pyroclastic flows, debris flows, and interbedded water-laid sediments, is between 40(?) million and 60(?) million years of age (McBirney and Williams 1965). The Padre Miguel Group, the result of the second episode of volcanism, is a thick sequence of ignimbrite similar to the Bandelier Tuff and is found throughout the southern half of Honduras; it is between 15 million and 20 million years of age (Williams and McBirney 1969).

This bare outline of the geology of Honduras will have to be filled in by studies of individual drill holes before we can infer with any confidence the nature of the plumbing system at each geothermal site.

Studies of Geothermal Sites

In the late 1970s several American firms began preliminary geothermal explorations in Honduras but were unable to complete them because of economic difficulties. These reconnaissance efforts allowed selection of six promising geothermal sites. However, the origin of the geothermal resource was misunderstood and incorrectly attributed to recent volcanism rather than, as our studies now indicate, to tectonic processes. Identification of the nature of the geothermal resource is a major contribution to the project. The amazing abundance of hot springs in Honduras suggests a large geothermal resource. Consequently, the project has two goals: selection of two geothermal sites for further development on the basis of detailed studies, by Los Alamos and ENEE geologists, of the six previously identified sites; and identification of other promising geothermal sites on the basis of a country-wide inventory of hot springs by ENEE with technical support, as necessary, from Los Alamos.

Detailed geologic studies have so far been carried out at three sites: Platanares, San Ignacio, and Azacualpa. Concurrently a team of geochemists from the Laboratory, the U.S. Geological Survey, and ENEE has sampled and analyzed the thermal waters to determine their chemistry and estimate the temperatures of the geothermal resevoirs (see "Geochemistry at Honduran Geothermal Sites").



Fault block mountains on the east side of Lago de Yojoa, Honduras.

Platanares. This site, located in the western portion of Honduras, is similar to many being developed in the Basin and Range province of Nevada. That is, water is heated deep underground and rises to the surface along faults. The numerous hot springs at Platanares are found in lavas, tuffs, and tuffaceous sediments of the Padre Miguel Group. The faults appear to be extensional, and the presence of wedges of gravel perched above the present water level in the Quebrada del Agua Caliente (Gorge of Hot Water) suggests relatively recent movement on these faults. The hottest springs are associated with faults that trend mostly northwest and north. Thermal energy is being released from boiling springs and numerous fumaroles. Since the stream that flows through the gorge is 10 to 15°C hotter in the area of the hot springs than it is upstream, additional energy is probably being released from submerged springs. Estimates of the thermal power of this area are given in "Geochemistry at Honduran Geothermal Sites."

San Ignacio. This site, located on the north side of the fault-bounded Siria Valley, also appears to be a geothermal system of the Basin and Range type. Hot springs are located at the intersection of a young northwest-trending fault scarp with older north-trending faults. These faults are also extensional, and, again, recently cut deposits of stream gravel suggest recent movement. The rocks within the area are primarily Paleozoic metamorphic schists containing some remnant patches of Padre Miguel Group tuffs. More than one hundred springs were mapped, many of which surface in terraces formed in deposits of silica-cemented gravel.

Azacualpa. This site, located in highly faulted sedimentary rocks that bound a major fault basin (the Santa Barbara graben), also appears to be a geothermal system of the Basin and Range type. The hot springs and fumaroles are surfacing along segments of the Zacapa fault, which cuts limestones and redbeds of Cretaceous age.

A view of the Platanares geothermal site in Copán, Honduras. Water from the hot springs enters the stream in the foreground, which flows through the Quebrada del Agua Caliente. Note the clouds of steam rising from individual fumaroles.

Summary

Our studies so far suggest that the geothermal manifestations in Honduras originate in a Basin and Range type of geothermal system, in which meteoric water (rainwater) flows downward along extensional faults, is heated, and rises back to the surface along other faults. In the Basin and Range geothermal systems in the United States, the heat is a by-product of the elevated geothermal gradient that develops when the earth's crust has been thinned by tectonic processes. We suspect the same heat source is responsible for the geothermal systems in Honduras, since the Padre Miguel Group of volcanic rocks is too old for residual heat to be the source of thermal energy.

Geophysical surveys are being planned for the spring of 1986 to answer questions about the size, depth, and location of the geothermal reservoirs, the regional heat flow, and the thickness of the crust. Plans are also under way to begin drilling shallow (about 500-meter) boreholes to measure the geothermal gradient. By combining all this information, we should be able to estimate the size and quality of the geothermal resources and to make recommendations to ENEE for future exploitation. ■

Participants in the geologic studies (and their institutional affiliations, if other than Los Alamos National Laboratory) are Jim Aldrich, Scott Baldridge, Wendell Duffield (U.S. Geological Survey), Dean Eppler, Bob Fakundiny (New York State Geological Survey), Richard Finch (Tennessee Technological University), Wilmer Flores (ENEE), Grant Heiken, Rodrigo Paredes (ENEE), Frank Perry, Napolen Ramos (ENEE), Alexander Ritchie (College of Charleston), and Ken Wohletz.

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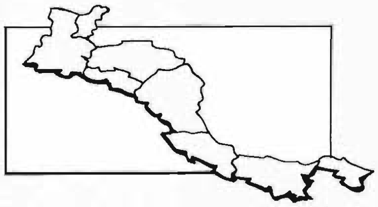
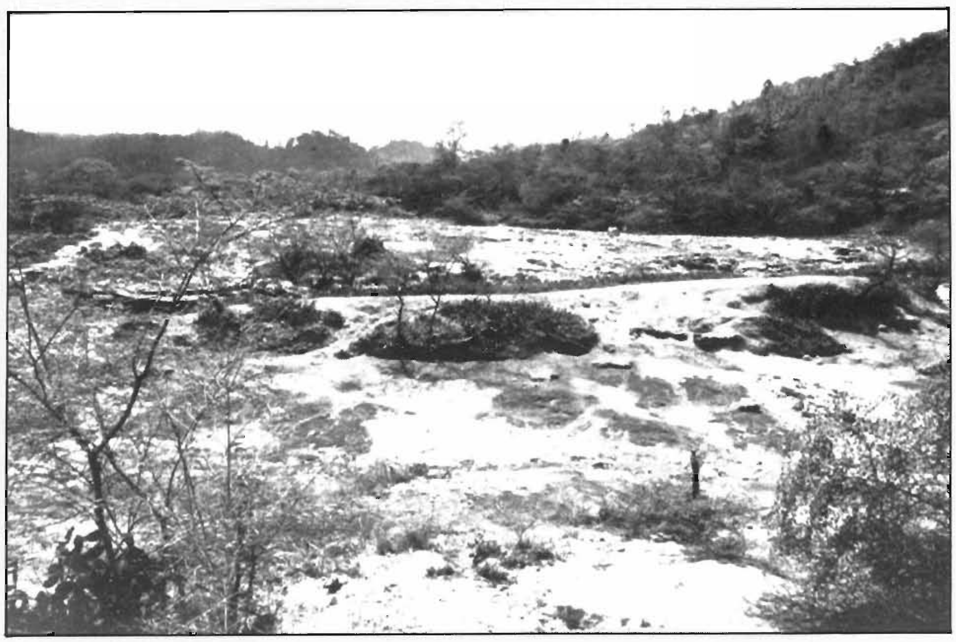


Geochemistry at Honduran Geothermal Sites

by Fraser Goff, C. O. Grigsby, Lisa A. Shevenell, and J. Wilfred Gutierrez

In May 1985 a team from Los Alamos National Laboratory, the United States Geological Survey, and the Empresa Nacional de Energía Eléctrica (ENEE) carried out hydrogeochemical studies at six major hot-spring systems in the western half of Honduras. The locations of these systems are noted on the map in "Geology of Honduran Geothermal Sites." The team analyzed water samples for concentrations of major and trace elements, stable isotopes, and tritium, gas samples for concentrations of carbon dioxide, hydrogen sulfide, methane, and other gases, and rock samples for concentrations of carbon and oxygen isotopes. The results of the analyses were used to assess the suitability of the sites for geothermal development. The team also studied many cold springs throughout Honduras to obtain background information about the concentrations of deuterium, tritium, and oxygen-18 in Central American waters.



View east of the silica sinter terrace at San Ignacio, Honduras. Boiling springs, which are used for cooking, discharge all around the perimeter of the 100- by 150-meter terrace. (Photo by Fraser Goff.)

View north of the La Cueva area, Azacualpa, Honduras. Note the steam from boiling springs at the mouth of the cave, which is formed of old carbonate travertine undercut by the creek in the foreground. (Photo by Fraser Goff.)

Table 1

Concentrations of silica, arsenic, lithium, boron, bromine, and ammonium in surface waters at six Honduran hot-spring sites and the temperatures of those surface waters. High surface concentrations of these species may indicate high temperatures in the underground reservoirs. Also listed, for comparison, are the concentrations found in a fluid sample from the Valles Caldera geothermal site in New Mexico. This sample was collected at a depth of 1500 meters (at the entry to Baca well #13); the temperature of the fluid there, after being corrected for steam flash, is 278°C.

Site	Hot-Spring Temperature (°C)	Concentration (mg/l) SiO_2	As	Li	B	Br	NH_4
Azacualpa	115.4	211	0.07	0.94	1.59	<0.1	1.09
El Olivar	75.9	120	<0.05	1.38	8.02	0.3	10.00
Pavana	101.8	128	0.11	0.27	1.43	<0.1	0.17
Platanares	99.5	288	1.26	4.04	16.70	<0.1	10.40
Sambo Creek	99.5	133	<0.05	0.17	0.09	<0.1	0.12
San Ignacio	99.0	214	<0.05	1.44	3.81	<0.5	2.78
Valles Caldera		488	1.16	17.20	14.90	5.3	1.52

The six sites studied were Azacualpa, El Olivar, Pavana, Platanares, Sambo Creek, and San Ignacio. Geologic evidence indicates that the hot-spring systems in Honduras are not associated with recent silicic volcanism, as is the case, for example, at Yellowstone National Park in Wyoming and the Valles Caldera in New Mexico. Rather, the setting in Honduras resembles that of Nevada: water circulates deep into the earth, is heated conductively, and rises convectively along faults and fractures. In agreement with the geologic evidence, the surface waters were found not to be acid-sulfate in character, which is indicative of an origin in near-surface steam reservoirs, and to be instead neutral to alkaline-chloride in character, which is indicative of an origin in subsurface reservoirs. Boiling and/or superheated hot springs are present at all sites except El Olivar; the temperature of the springs there is less than 76°C. Several of the spring systems have deposited silica (SiO_2) as terraces or as gravel cements, a feature that usually indicates subsurface reservoir temperatures greater than 150°C.

The concentrations of certain chemical constituents in the surface waters at a geothermal site depend primarily on the subsurface reservoir temperature and the rock type and to a lesser extent on the amount of circulating water and the flow rate. Significant concentrations of silica, arsenic, lithium, boron, bromine, and ammonium, for example, usually indicate a high equilibrium temperature in the reservoir. Table 1 lists the concentrations of these constituents in typical water samples from the six Honduran sites and, for comparison, in a sample from a reservoir in the Valles Caldera of New Mexico, which is known to contain high-temperature fluid. We use the Valles Caldera for comparison because it is a classic geothermal system, well known among geologists, and its rock types are very similar to those found at the Honduran sites (primarily welded tuffs and ancient sedimentary rocks such as limestones, sandstones, and shales). Nevertheless, since the Valles

Caldera fluid is generated in a volcanic environment and, in addition, the sample for that reservoir came from a very-high-temperature well, only qualitative conclusions can be drawn from such a comparison. The data suggest that the Platanares site is the hottest of the six Honduran sites but is not as hot as the Valles Caldera reservoir.

A better way to assess equilibrium reservoir temperatures is to use chemical geothermometers. Table 2 lists, for the six Honduran sites and for the Valles Caldera, the subsurface reservoir temperatures estimated with two widely used geothermometers, quartz and sodium-potassium-calcium. The quartz geothermometer relates quartz (SiO_2) concentration to temperature through the laboratory-measured solubility curve of this mineral. The solubility of quartz rises steeply between 100 and 300°C. Since precipitation is quite sluggish with falling temperature, the silica concentrations found in the surface waters are good indicators of the subsurface reservoir temperature. The sodium-potassium-calcium geothermometer, an empirical relation between relative concentrations of these elements in surface water and reservoir temperatures, is based on data gathered from many high-temperature geothermal systems around the world. The Platanares site again comes out ahead, but the temperatures of two other sites, San Ignacio and Azacualpa, are greater than 180°C, the minimum temperature required for economical generation of electric power.

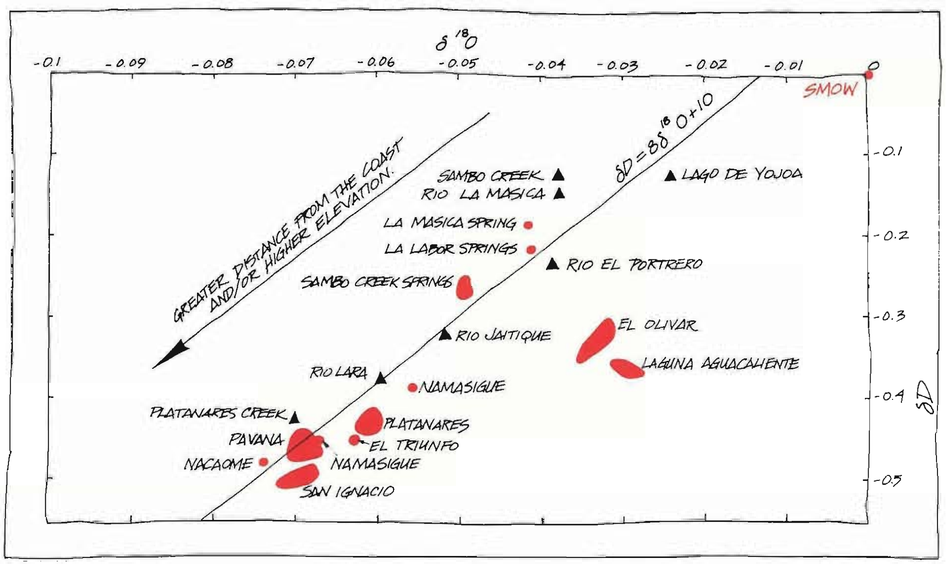
Our results from chemical geothermometry generally agree with those from gas geothermometry. One gas geothermometer uses the relative concentrations of carbon dioxide, hydrogen sulfide, methane, and hydrogen as an indicator of temperature. The relationship is empirical but has been supported by theoretical studies of equilibration among these gases at high temperature and by comparison with the gas chemistry of many explored geothermal fields.

Table 3 lists the minimum electric

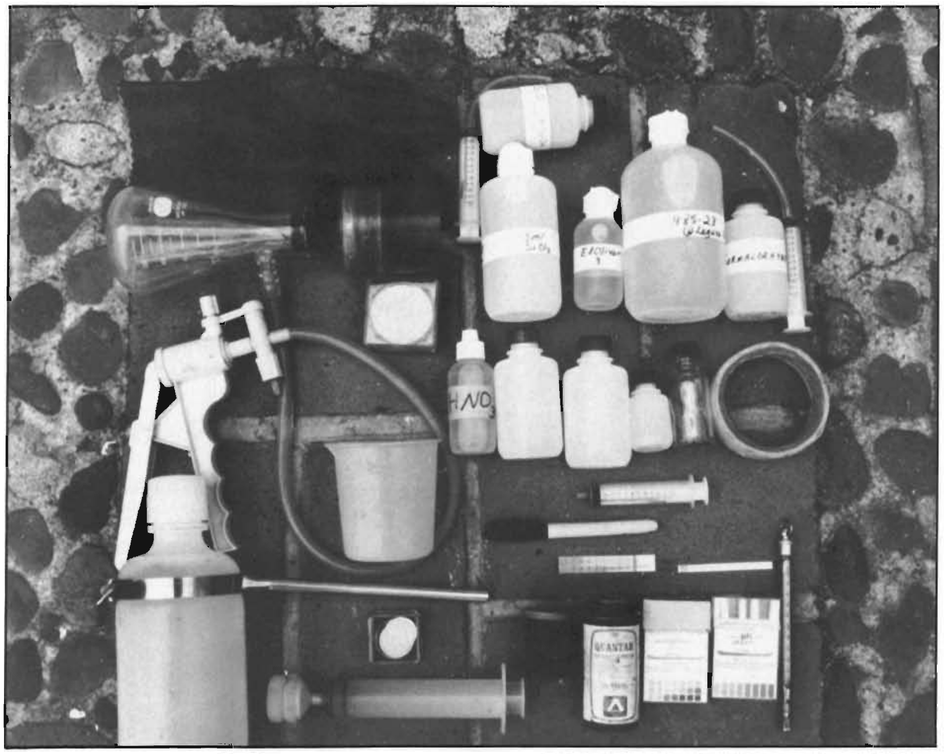
Table 2

Estimated temperatures of the underground reservoirs at six Honduran hot-spring sites. These estimates were obtained by using two chemical geothermometers, the quartz and the sodium-potassium-calcium geothermometers (see text). Also listed are similar estimates for the temperature of the underground reservoir at the Valles Caldera geothermal site in New Mexico. The observed temperature of the Valles Caldera fluid, measured at a depth of 1500 meters (at the entry to Baca well #13) and corrected for steam flash, is 278°C.

	Estimated Reservoir Temperature (°C)	
Site	**Quartz Geothermometer**	**Na-K-Ca Geothermometer**
Azacualpa	184	181
El Olivar	148	101
Pavana	151	138
Platanares	207	225
Sambo Creek	147	148
San Ignacio	185	208
Valles Caldera	249	282



Results of isotopic analyses of water samples from hot springs (red) and lakes, rivers, and cold streams (black) in Honduras. Shown is a plot of $\delta D = (^2H/^1H)_{sample} - (^2H/^1H)_{SMOW}$ versus $\delta^{18}O = (^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{SMOW}$, where ^2H, ^1H, ^{18}O, and ^{16}O are isotopic concentrations and SMOW stands for standard mean ocean water. Data points for all surface waters worldwide are found to fall near the line $\delta D = 8\delta^{18}O + 10$. The distance along that line between the data point for SMOW and the data point for a sample is indicative of the distance from the ocean and the elevation of the sample's origin. These isotopic analyses indicate that the Honduran geothermal reservoirs contain recycled rainwater from the local area around each site.



Some of the lightweight, compact equipment used to collect samples of water from hot springs. Six samples are collected from a spring, one each for anion, cation, tritium, deuterium and oxygen-18 (as water), carbon-13, and oxygen-18 (as sulfate) analysis. The samples for anion and cation analysis are filtered through a 0.45-micrometer filter; the sample for cation analysis is acidified with HNO_3 to a pH less than 2; the sample for carbon-13 analysis is treated with saturated $SrCl_2$ and concentrated NH_4OH to precipitate $SrCO_3$; and the sample for analysis of oxygen-18 as sulfate is treated with formaldehyde to preserve the sulfate. Conductivity, temperature, pH, and chloride are measured at the site. Gas sampling requires a different array of equipment.

Table 3

Estimates of thermal power and equivalent electrical power from surface discharges at six Honduran hot-spring sites. Also listed are values for the parameters involved in the estimates: the estimated surface discharge rates, the best available estimates for the temperatures of the underground reservoirs, and the ambient temperatures. The thermal power was approximated as the product of surface discharge rate and the difference between the heat content of the fluid at the temperature of the reservoir and at ambient temperature. An efficiency of 20 percent was assumed for the conversion of thermal power to electrical power, which is practical only if the reservoir temperature exceeds 180°C. The power potential of these sites may be much greater than these estimates of power from surface discharges.

Site	Estimated Surface Discharge (l/min)	Estimated Reservoir Temperature (°C)	Ambient Temperature (°C)	Thermal Power (MW)	Electrical Power (MW)
Platanares	3150	225	27	44.9	9
San Ignacio	1200	190	28	13.8	2.8
Azacualpa	1200	185	28	13.4	2.5
Pavana	1000	145	30	8.1	---
Sambo Creek	2000	150	30	16.9	---
El Olivar	200	120	30	1.3	---

power potential of these sites based on the estimated reservoir temperatures and the estimated surface discharge rates. Here too, Platanares looks very promising.

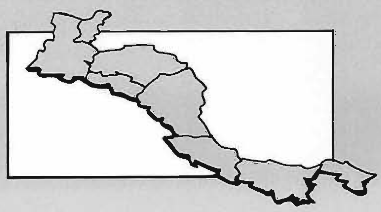
Ratios of deuterium to hydrogen-1 concentrations and oxygen-18 to oxygen-16 concentrations in a water sample provide information about the source of the water. Measured values of these isotopic ratios in samples of surface water from the Honduran geothermal sites indicate that recycled rainwater is feeding the reservoirs (see accompanying figure).

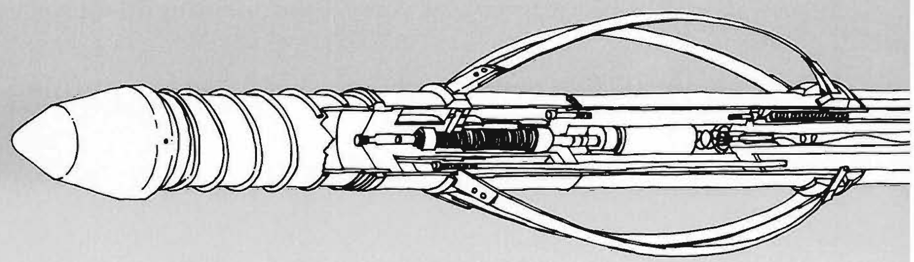
The tritium content of a geothermal fluid can be related to its age through equations describing the circulation of fluids in the geothermal system. The equations include the known input of tritium from the atmosphere as a function of time and location of the system. Analytical solution of the equations indicates that Honduran geothermal waters are between 34 and 7500 years old and are most likely several thousand years old. The better sites should therefore provide a stable, long-lasting source of geothermal power.

The ratio of carbon-13 to carbon-12 concentrations in a sample of surface water is an indicator of rock types through which the water flows. Measured values of this ratio in bicarbonate (HCO_3) from the Honduran hot springs indicate that the springs are flowing through sedimentary rocks and/or rocks containing hydrocarbons and other organic compounds.

By combining the information obtained from geochemical and geologic studies, the temperature and flow dynamics of a site can be evaluated before the more expensive step of drilling begins. ■

The geochemical work reported here was done by Dale Counce, Fraser Goff, Chuck Grigsby, Wilfred Gutierrez, Lisa Shevenell, and Pat Trujillo of Los Alamos National Laboratory, Alfred Truesdell and Cathy Janik of the U.S. Geological Survey (Menlo Park), and Rodrigo Paredes of ENEE.





High-Temperature Borehole Measurements at Miravalles, Costa Rica

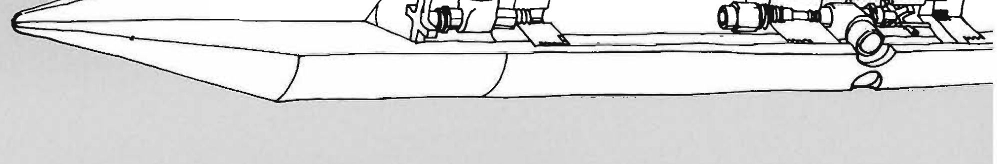
by Bert R. Dennis and Robert J. Hanold

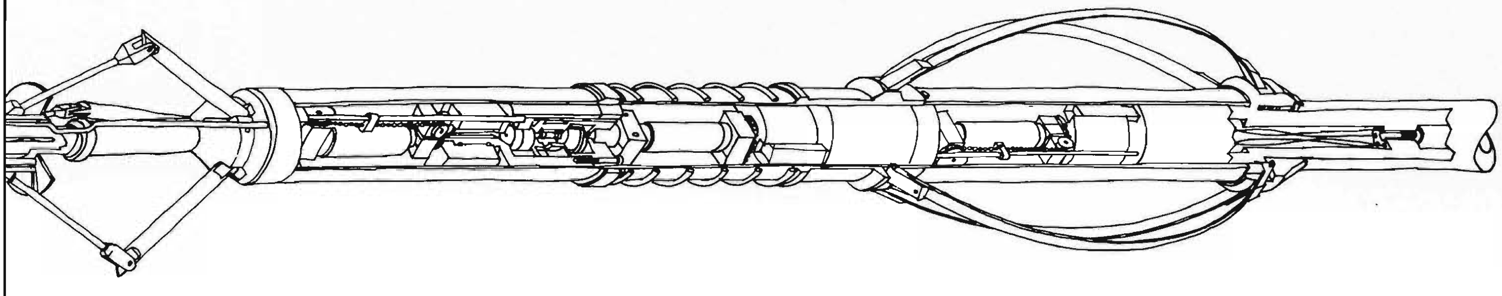
Well-logging equipment on site at the Miravalles geothermal field.

Costa Rica is developing its first geothermal power plant on the southern flank of the Miravalles Volcano in the Guanacaste Volcanic Range. If successful, this development will complement the vast hydroelectric resources of the country and help eliminate the need for fossil-fueled power plants. At present the import of petroleum contributes significantly to the trade imbalance of the country.

The development at Miravalles began about ten years ago with reconnaissance efforts, sponsored by the United Nations, that identified the slopes of Miravalles and Rincon de la Vieja volcanoes as potential sites for development of geothermal resources. The Power Planning Division of the Costa Rican Institute of Electricity (ICE) then began drilling deep production wells at Miravalles. The results were encouraging; the production wells have penetrated a 240°C-reservoir of geothermal brine at a depth of less than 2 kilometers, and the flow rates in the wells are very high (39 to 76 kilograms per second). So far so good. But when the initial wells were flow-tested, ICE engineers detected the presence of calcite ($CaCO_3$) deposits in the well bores. Since they lacked instruments to make measurements in the high-temperature environment downhole, they had no way to assess the scope of the problem.

Then, while attending a 1984 Los Alamos workshop for Central Americans on geothermal energy development, ICE engineers learned of the specialized instruments developed by the Laboratory's Earth Science Instrumentation Group to satisfy the diagnostic needs of the Los Alamos hot dry rock geothermal energy





▲Fig. 1. The three-arm caliper and contour tool developed at Los Alamos yields precision measurements of borehole dimensions and in situ casings. An electric motor extends or retracts the caliper arms on command from the surface logging rig.

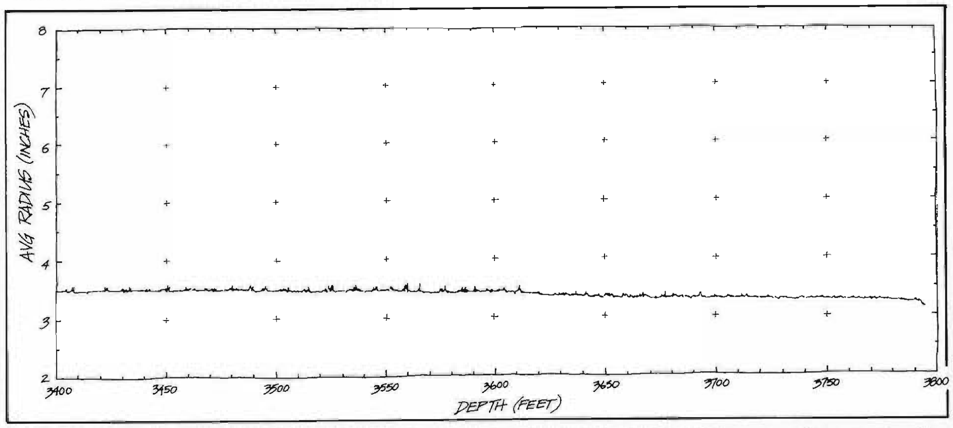


Fig. 3. Results of a caliper survey of a well at the Miravalles geothermal site. Accumulated scale deposits have caused a decrease in the inside radius of the slotted production liner from 3.5 inches at a depth of 3400 feet to 3.2 inches at 3800 feet. The slots in the production liner, which provide the passageway for the reservoir fluids into the production well, are evident in the caliper data at shallower depths but essentially disappear at depths below 3600 feet. These slots are apparently being plugged with calcite deposits.▲

program. These unique logging tools are capable of operating at temperatures up to 300°C and pressures up to 15,000 psi for durations between 8 and 30 hours. The Costa Ricans explained their problem, and with support from the U. S. Agency for International Development, these instruments were made available to ICE for downhole diagnostic measurements at the Miravalles wells.

Los Alamos engineers and technicians overhauled a surplus well-logging rig and equipped it with 3 kilometers of special cable and a cablehead assembly, designed at Los Alamos, for interfacing with the downhole tools. A computer-driven data-acquisition system was installed in the logging cab. After being tested in a local geothermal well, the unit was shipped to Costa Rica together with logging tools for measuring temperature and pressure as a function of depth, flow rate throughout the production layer, and the contour and average diameter of the well casing and for collecting samples of brine from the reservoir without loss of dissolved gases.

Two wells at the Miravalles field were logged. A single borehole instrument measured temperature, pressure, and flow rate. This new tool significantly increases the efficiency of measurements in a hot, high-pressure well because only a single entry and removal through the pressure lock is required. Figure 1 shows the tool used to measure the contour and average diameter of the well casing. Figure 2 shows the tool used to collect pressurized fluid samples at various locations in the well.

We are currently analyzing the logging data, and the brine samples are enroute to Los Alamos for chemical analysis. Bottom-hole temperatures in both wells approach 240°C, an excellent temperature for efficient generation of electricity.

The caliper surveys confirmed the suspicions of the ICE engineers by indicating considerable buildup of calcite in the lower sections of one of the wells (Fig. 3). Such deposits will ultimately reduce the flow rate from the well.

The initial logging experiences at Miravalles indicated the need for some modifications in the logging tools to improve their durability in the high-flow-rate wells. When these modifications are completed, the equipment will be returned to Costa Rica and used to log additional production wells. Data from these logging surveys could lead to an improved drilling strategy for the rest of the production wells. ■

Participants in the logging efforts included David Anderson, Gloria Bennett, Lynn Brewer, Pete Chavez, Benny Garcia, Ray Jermance, Jerome Kolar, Richard Maestas, and Evon Stephani of Los Alamos National Laboratory and Rodrigo Corrales and Manuel Corrales of ICE.

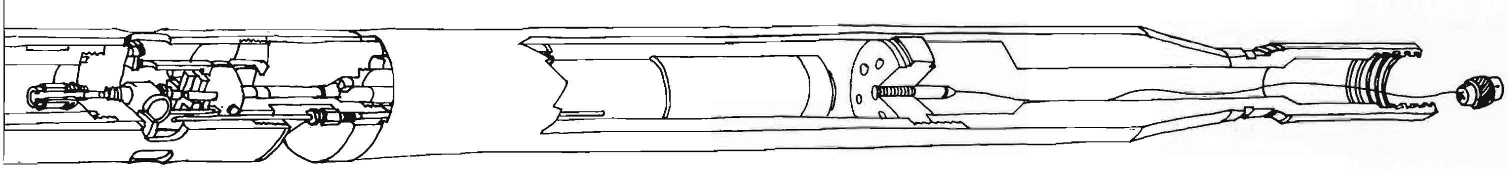


Fig. 2. The fluid sampler tool has two chambers for collecting samples. The motor that opens and closes the sample chambers is activated on command from the surface logging rig.▲